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Livschitz et al.

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(45) **Date of Patent: Jul. 7, 2015**

(54) **APPARATUS AND METHOD FOR DIMMING SIGNAL GENERATION FOR A DISTRIBUTED SOLID STATE LIGHTING SYSTEM**

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(73) Assignee: **Luxera, Inc.**, San Ramon, CA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 78 days.

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(22) Filed: **Oct. 18, 2013**

(65) **Prior Publication Data**

US 2014/0042933 A1 Feb. 13, 2014

Related U.S. Application Data

(63) Continuation-in-part of application No. 13/664,068, filed on Oct. 30, 2012.

(60) Provisional application No. 61/606,837, filed on Mar. 5, 2012.

(51) **Int. Cl.**
H05B 33/08 (2006.01)

(52) **U.S. Cl.**
CPC ***H05B 33/0848*** (2013.01); ***H05B 33/0818*** (2013.01); ***H05B 33/0851*** (2013.01)

(58) **Field of Classification Search**
None
See application file for complete search history.

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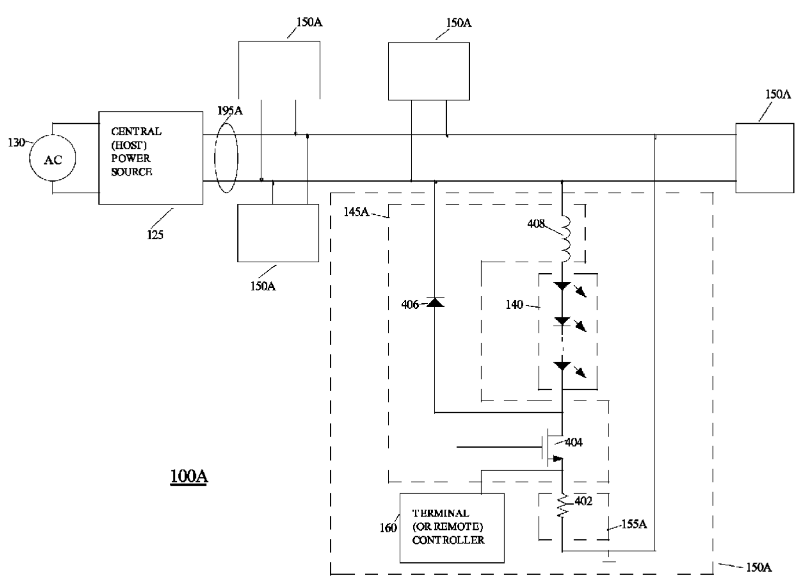
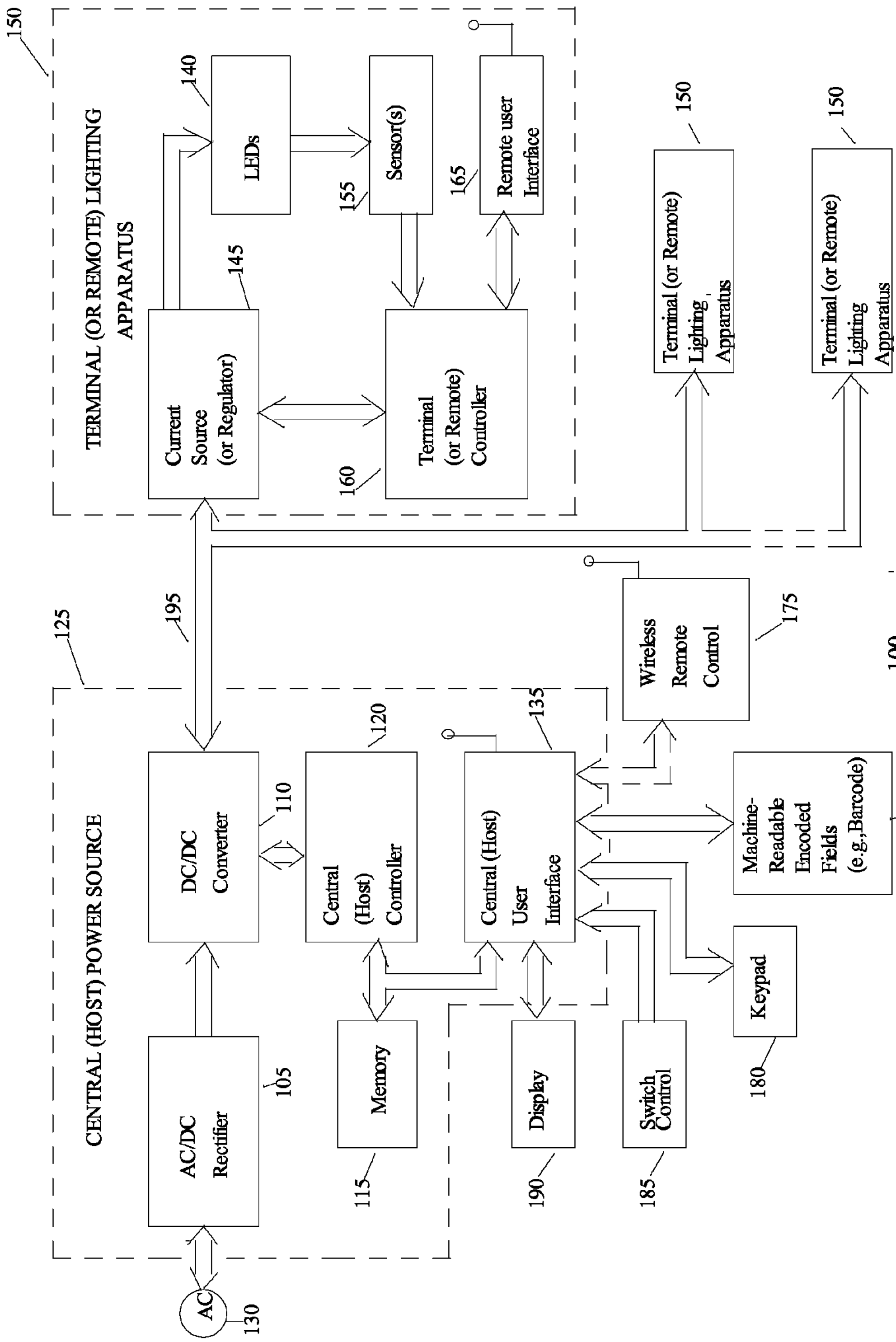
Primary Examiner — Crystal L Hammond
(74) *Attorney, Agent, or Firm* — Nancy R. Gamburd; Gamburd Law Group LLC

(57) **ABSTRACT**

Exemplary systems, methods and apparatuses for providing dimming in a distributed solid-state lighting system are disclosed. An exemplary dimming signal generator is coupleable to a controller or a current generator for a plurality of LEDs, and includes a first resistive voltage divider to sense an input DC voltage; a current sensor to sense a current level of the plurality of LEDs; a first operational amplifier to compare the sensed input DC voltage to a reference voltage level and to provide a comparator output signal; and a current path to combine the comparator output signal with the sensed LED current level to provide a combined signal for current level feedback for control of the LED current level. The dimming signal generator may optionally include other components to generate a PWM signal and also to provide a resistive network to divert LED current in response to the comparator output signal.

25 Claims, 27 Drawing Sheets




150
TERMINAL (OR REMOTE) LIGHTING APPARATUS
140
LEDs
Sensor(s)
155
Remote user Interface
165
145
Current Source (or Regulator)
Terminal (or Remote) Controller
160
150
Terminal (or Remote) Lighting Apparatus
150
Terminal (or Remote) Lighting Apparatus
195
125
CENTRAL (HOST) POWER SOURCE
DC/DC Converter
110
120
Central (Host) Controller
135
Central (Host) User Interface
Wireless Remote Control
175
Machine-Readable Encoded Fields (e.g.,Barcode)
170
Keypad
180
AC/DC Rectifier
105
Memory
115
Display
190
Switch Control
185
AC
130

100

FIG. 1

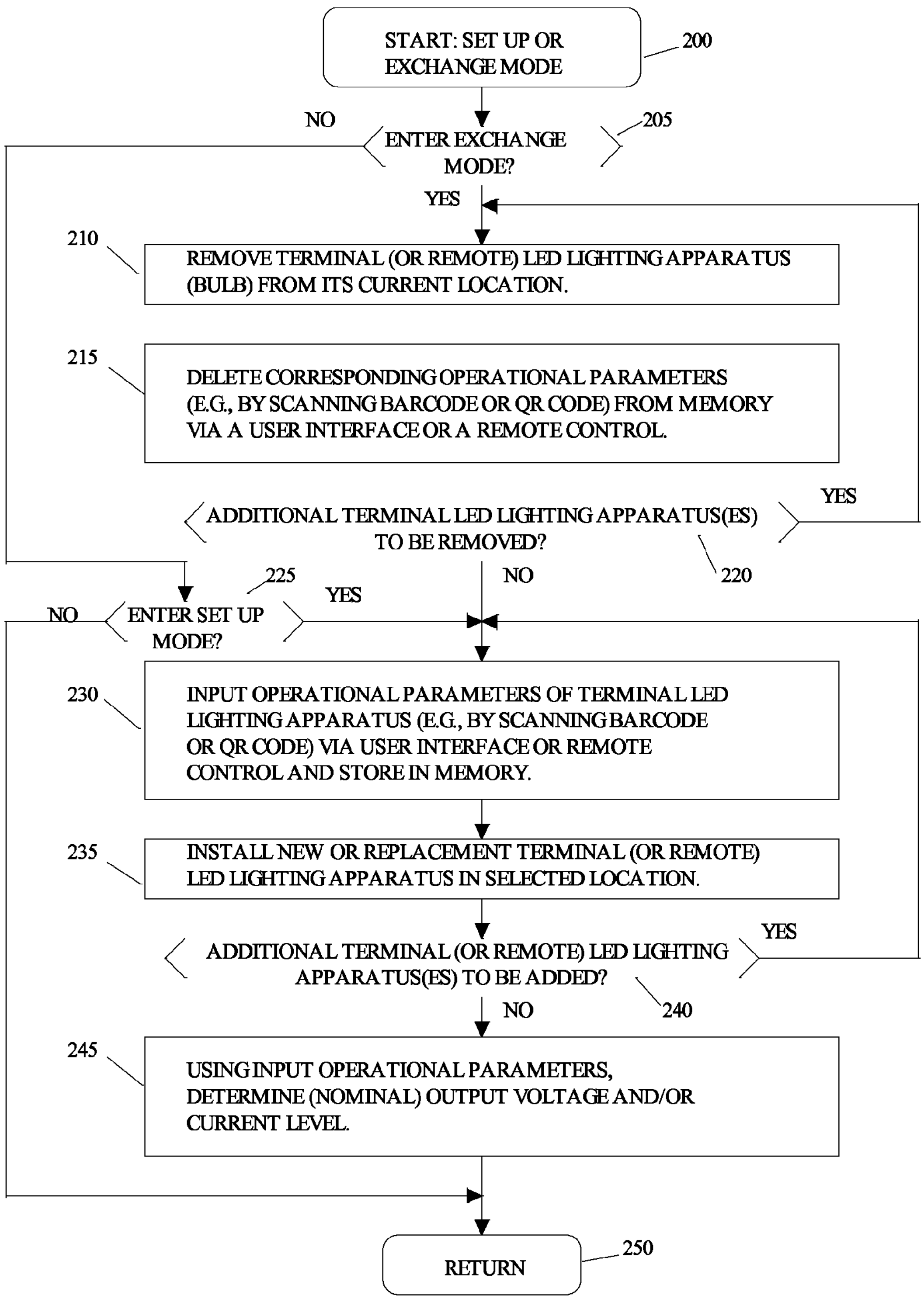

START: SET UP OR EXCHANGE MODE
200
ENTER EXCHANGE MODE?
205
NO
YES
210
REMOVE TERMINAL (OR REMOTE) LED LIGHTING APPARATUS (BULB) FROM ITS CURRENT LOCATION.
215
DELETE CORRESPONDING OPERATIONAL PARAMETERS (E.G., BY SCANNING BARCODE OR QR CODE) FROM MEMORY VIA A USER INTERFACE OR A REMOTE CONTROL.
ADDITIONAL TERMINAL LED LIGHTING APPARATUS(ES) TO BE REMOVED?
YES
NO
220
225
ENTER SET UP MODE?
NO
YES
230
INPUT OPERATIONAL PARAMETERS OF TERMINAL LED LIGHTING APPARATUS (E.G., BY SCANNING BARCODE OR QR CODE) VIA USER INTERFACE OR REMOTE CONTROL AND STORE IN MEMORY.
235
INSTALL NEW OR REPLACEMENT TERMINAL (OR REMOTE) LED LIGHTING APPARATUS IN SELECTED LOCATION.
ADDITIONAL TERMINAL (OR REMOTE) LED LIGHTING APPARATUS(ES) TO BE ADDED?
YES
NO
240
245
USING INPUT OPERATIONAL PARAMETERS, DETERMINE (NOMINAL) OUTPUT VOLTAGE AND/OR CURRENT LEVEL.
RETURN
250

FIG. 2

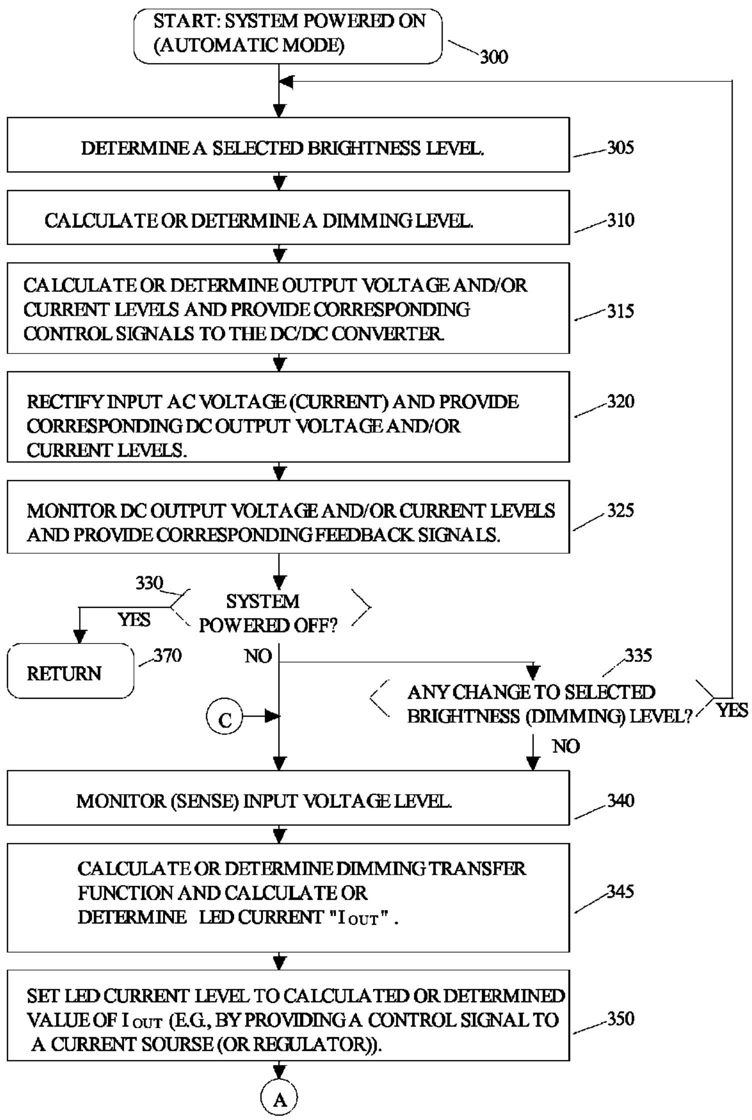

START: SYSTEM POWERED ON (AUTOMATIC MODE)
300
DETERMINE A SELECTED BRIGHTNESS LEVEL.
305
CALCULATE OR DETERMINE A DIMMING LEVEL.
310
CALCULATE OR DETERMINE OUTPUT VOLTAGE AND/OR CURRENT LEVELS AND PROVIDE CORRESPONDING CONTROL SIGNALS TO THE DC/DC CONVERTER.
315
RECTIFY INPUT AC VOLTAGE (CURRENT) AND PROVIDE CORRESPONDING DC OUTPUT VOLTAGE AND/OR CURRENT LEVELS.
320
MONITOR DC OUTPUT VOLTAGE AND/OR CURRENT LEVELS AND PROVIDE CORRESPONDING FEEDBACK SIGNALS.
325
330
SYSTEM POWERED OFF?
YES
RETURN
370
NO
335
ANY CHANGE TO SELECTED BRIGHTNESS (DIMMING) LEVEL?
YES
NO
C
MONITOR (SENSE) INPUT VOLTAGE LEVEL.
340
CALCULATE OR DETERMINE DIMMING TRANSFER FUNCTION AND CALCULATE OR DETERMINE LED CURRENT "I OUT".
345
SET LED CURRENT LEVEL TO CALCULATED OR DETERMINED VALUE OF I OUT (E.G., BY PROVIDING A CONTROL SIGNAL TO A CURRENT SOURSE (OR REGULATOR)).
350
A

FIG. 3A

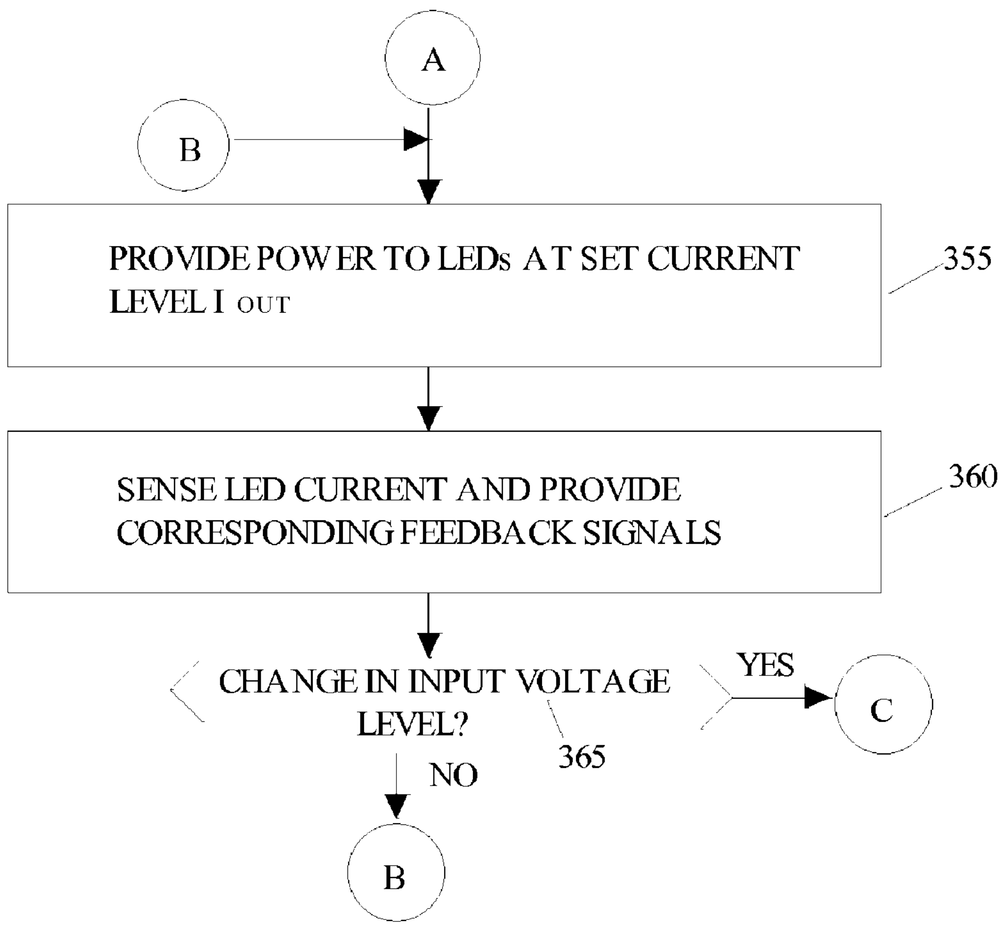

A
B
PROVIDE POWER TO LEDs AT SET CURRENT LEVEL I OUT
355
SENSE LED CURRENT AND PROVIDE CORRESPONDING FEEDBACK SIGNALS
360
CHANGE IN INPUT VOLTAGE LEVEL?
365
YES
C
NO
B

FIG. 3B

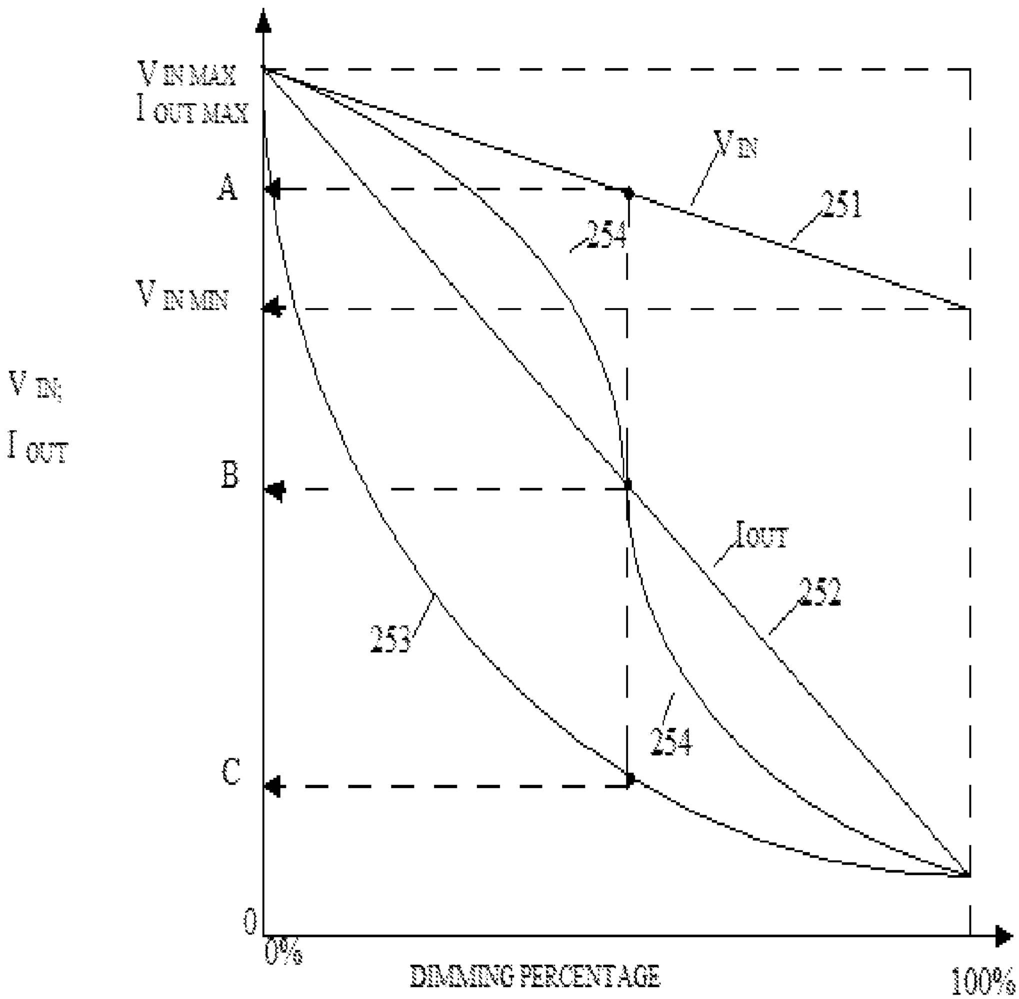

V IN MAX
I OUT MAX
A
V IN MIN
V IN;
I OUT
B
C
0
0%
DIMMING PERCENTAGE
100%
V IN
251
254
I OUT
252
253
254

FIG. 4

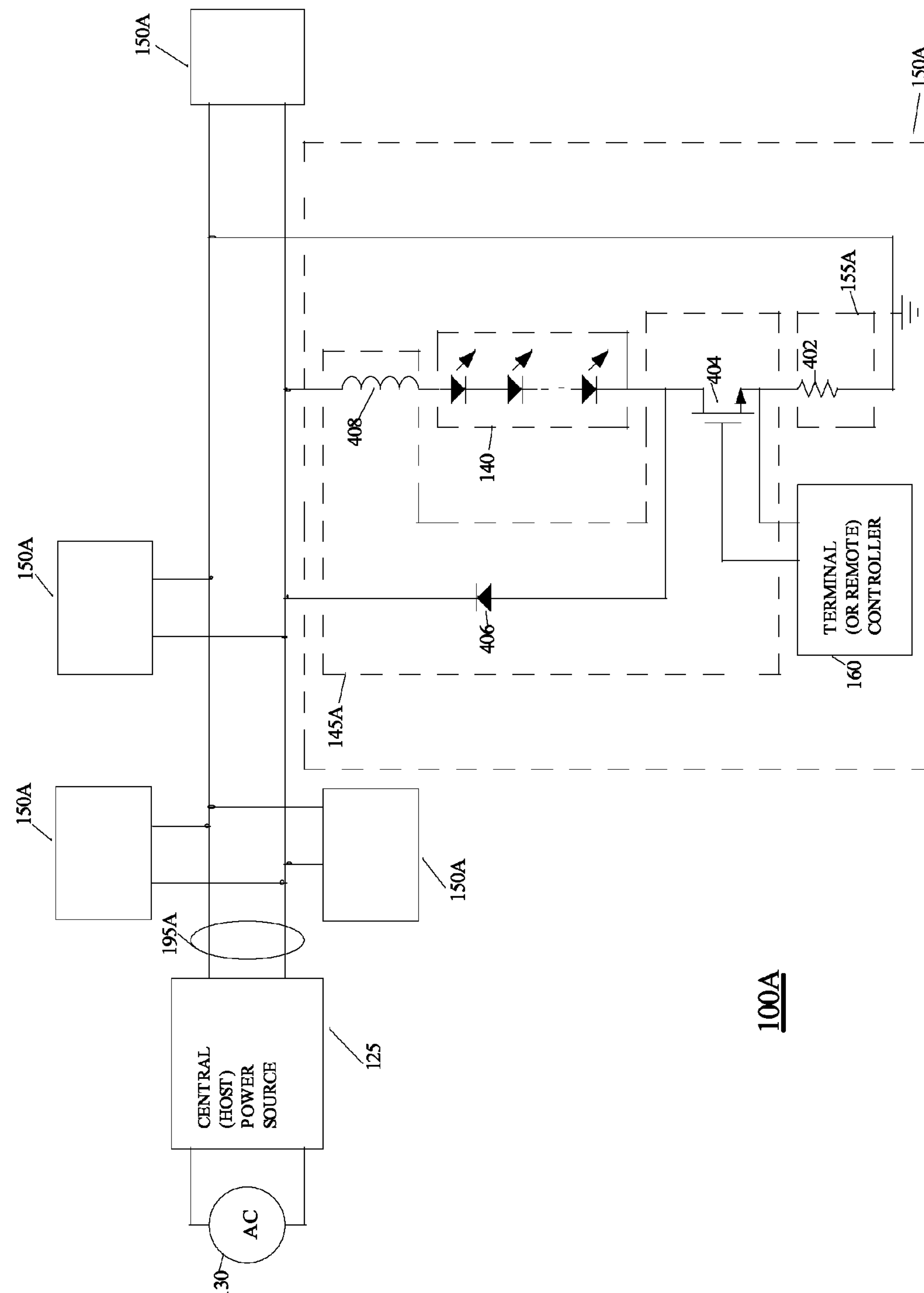

150A
150A
155A
402
404
408
140
150A
406
145A
TERMINAL
(OR REMOTE)
CONTROLLER
160
150A
150A
195A
CENTRAL
(HOST)
POWER
SOURCE
125
AC
130
100A

FIG. 5

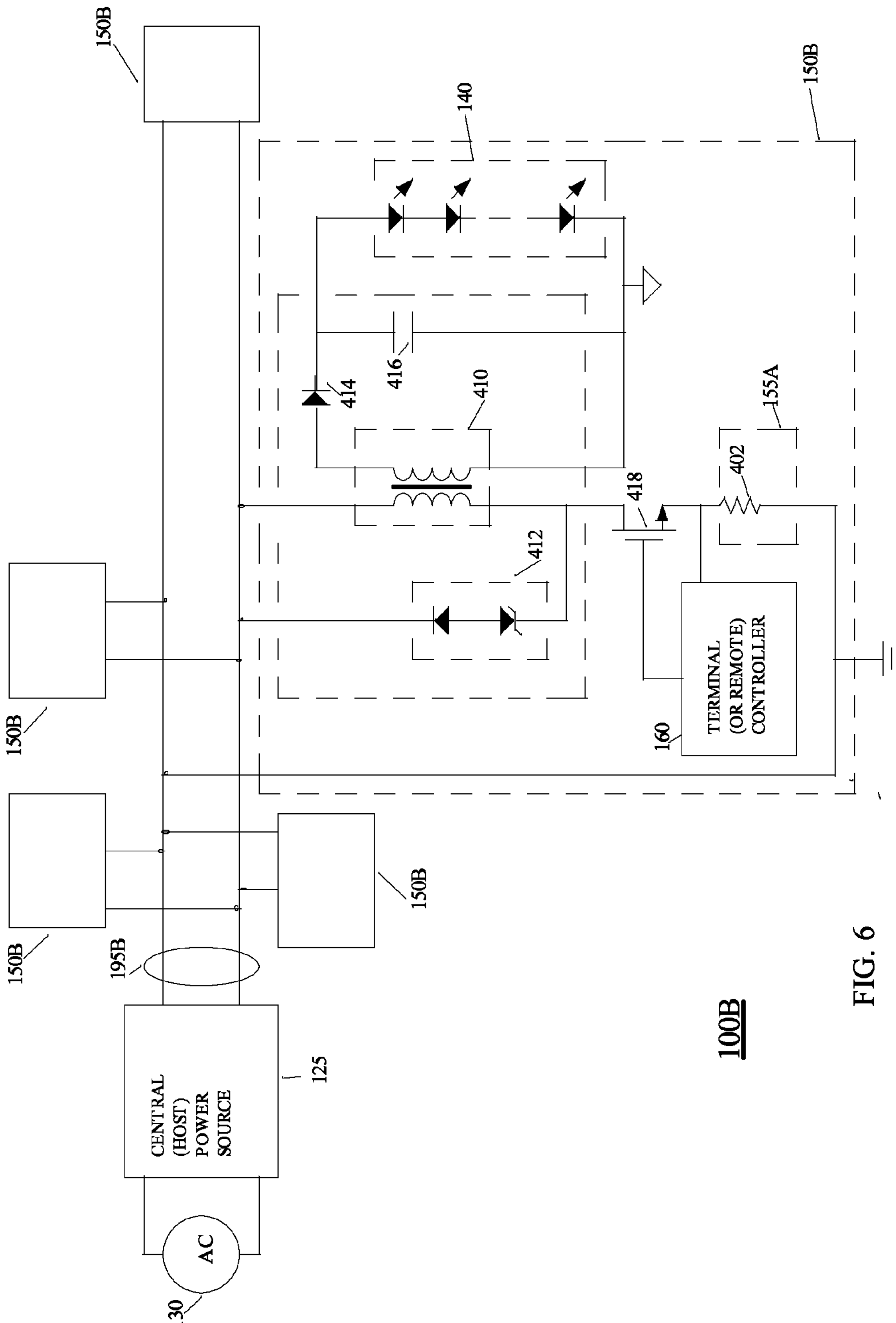

150B
140
150B
414
416
410
155A
402
418
412
TERMINAL
(OR REMOTE)
CONTROLLER
160
150B
150B
150B
195B
150B
CENTRAL
(HOST)
POWER
SOURCE
125
AC
130
100B

FIG. 6

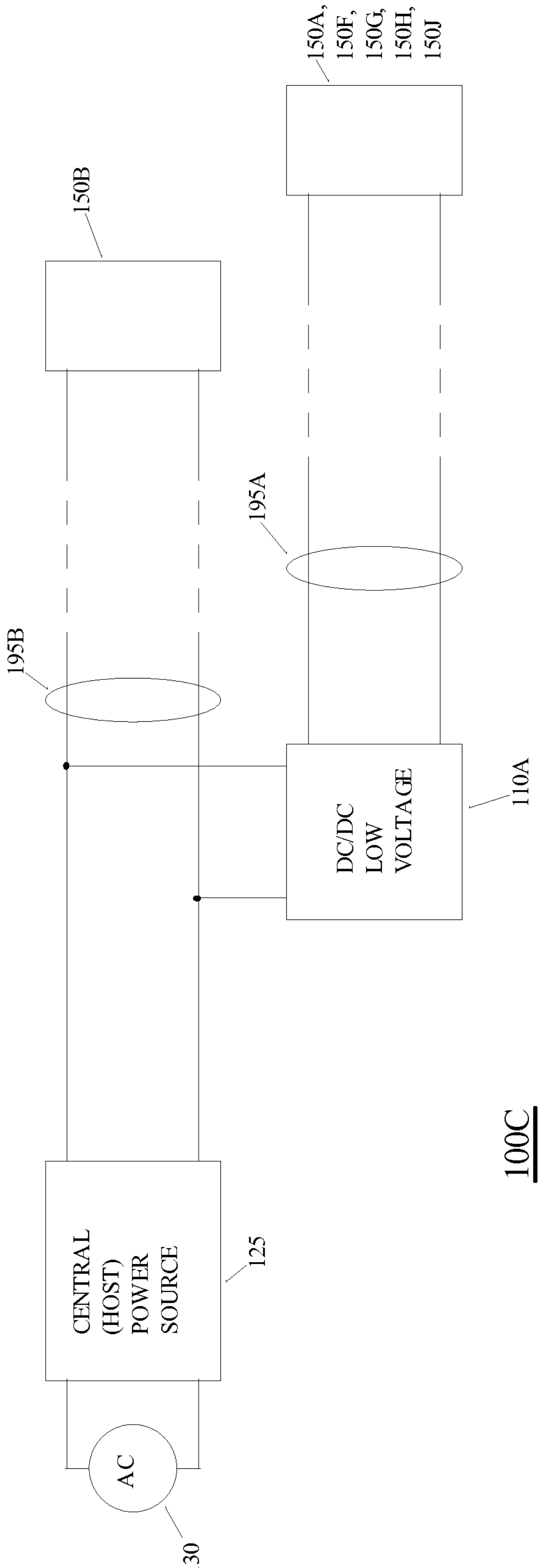

150A, 150F, 150G, 150H, 150J
150B
195A
195B
DC/DC LOW VOLTAGE
110A
CENTRAL (HOST) POWER SOURCE
125
AC
130
100C

FIG. 7

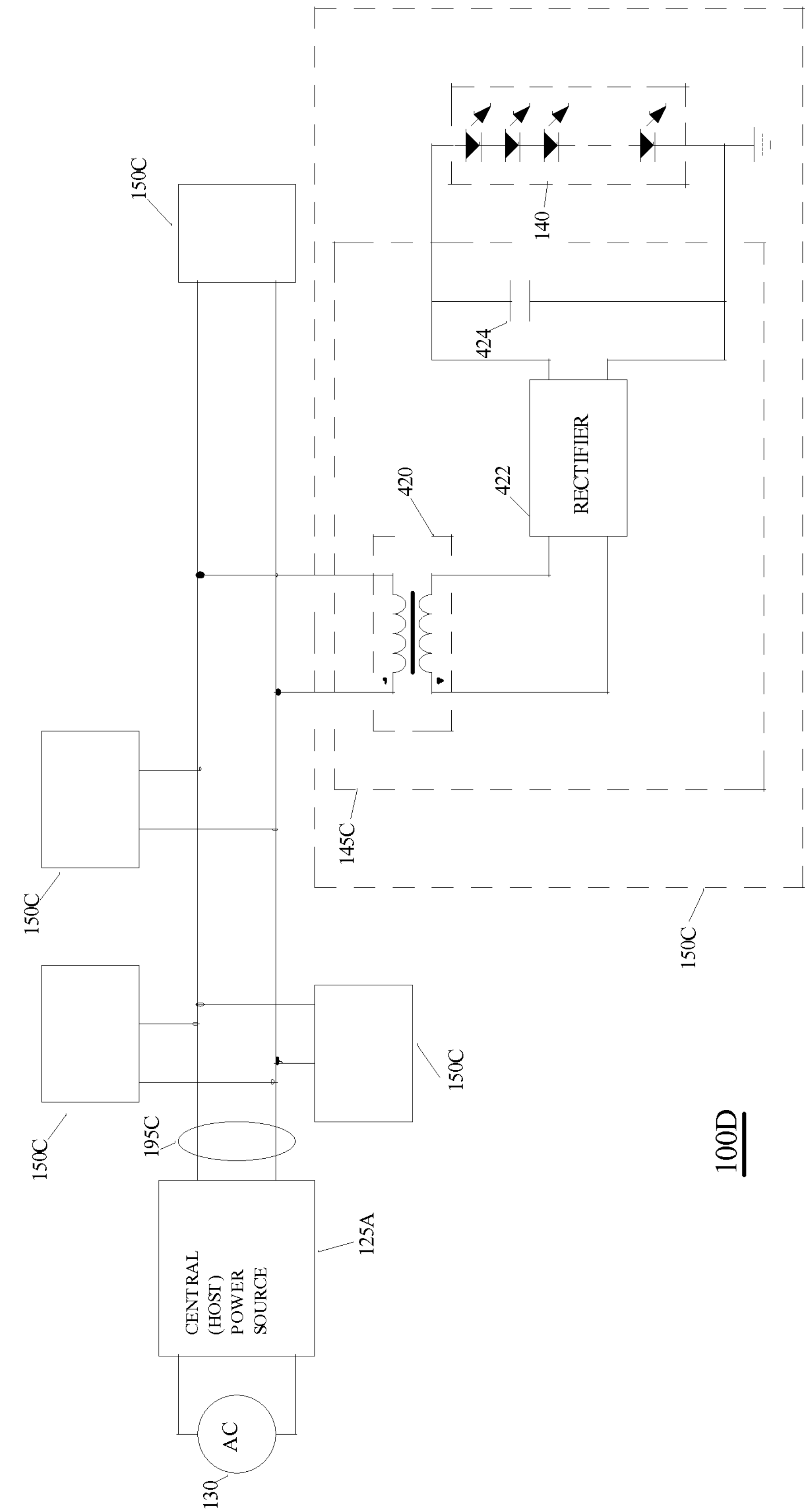

150C
140
424
420
422
RECTIFIER
145C
150C
150C
150C
150C
195C
150C
125A
CENTRAL (HOST) POWER SOURCE
AC
130
100D

FIG. 8

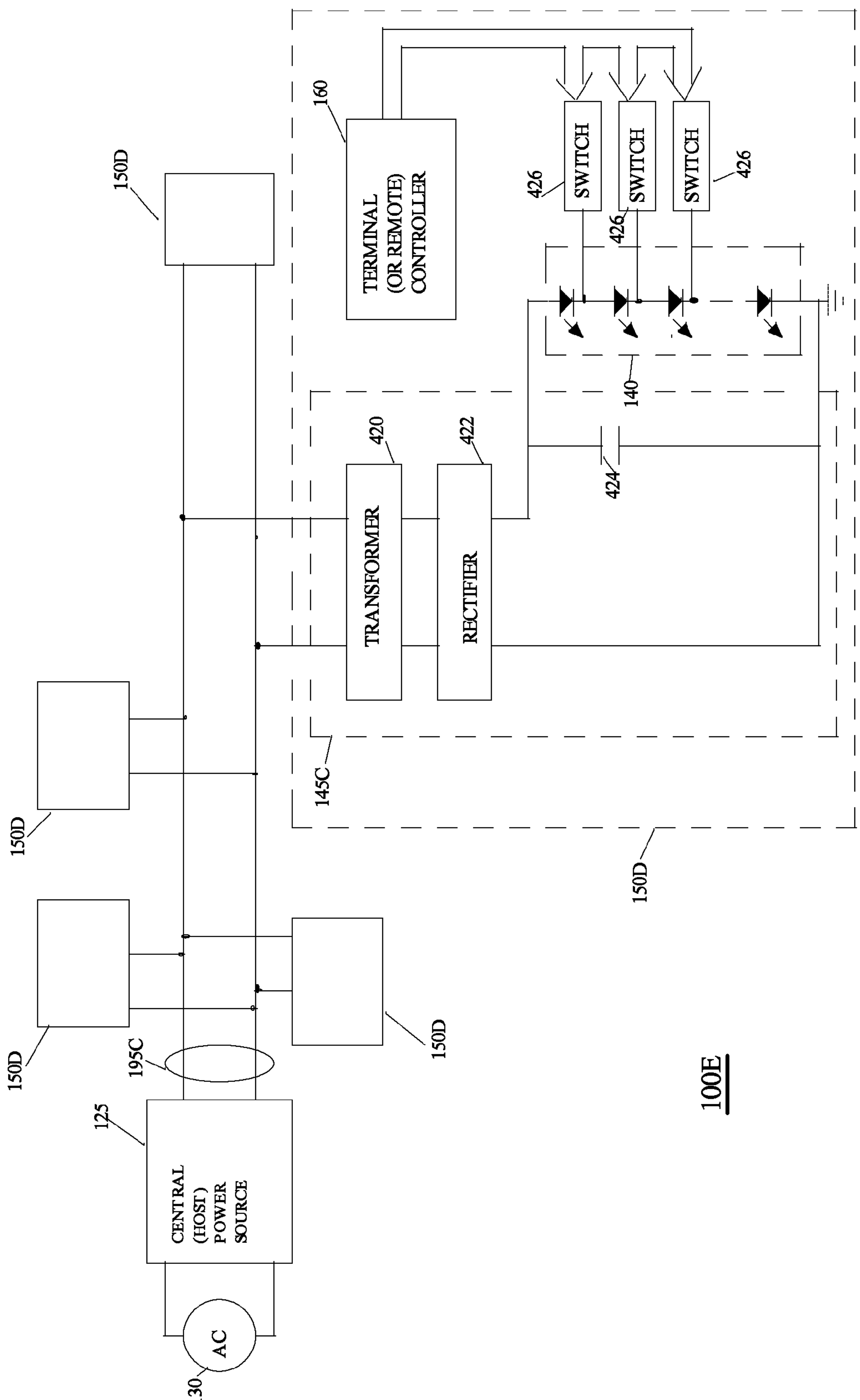

150D
160
TERMINAL
(OR REMOTE)
CONTROLLER
SWITCH
SWITCH
SWITCH
426
426
426
140
420
422
TRANSFORMER
RECTIFIER
424
145C
150D
150D
150D
150D
195C
125
CENTRAL
(HOST)
POWER
SOURCE
AC
130
100E

FIG. 9

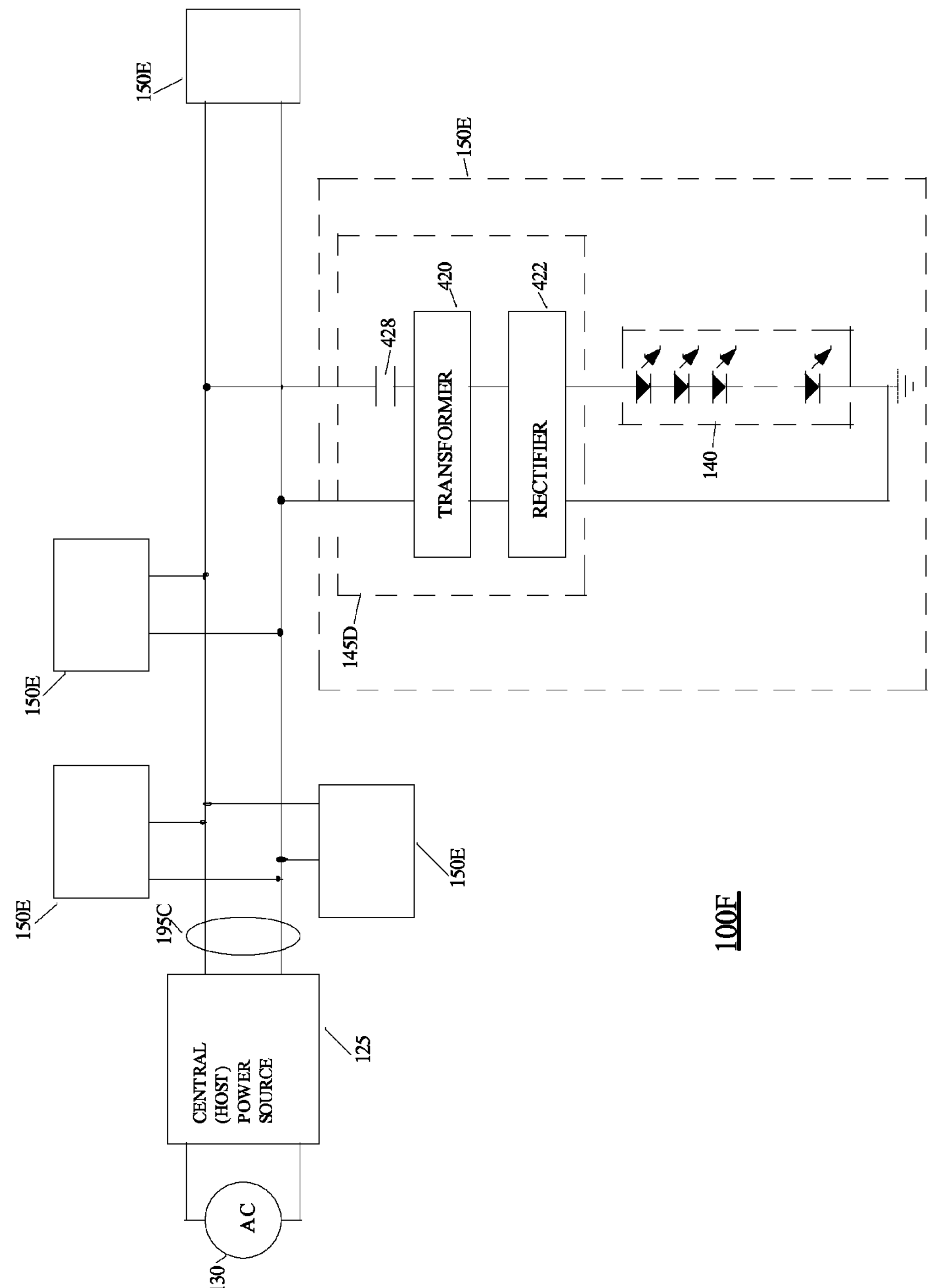

150E
150E
420
422
428
TRANSFORMER
RECTIFIER
140
145D
150E
150E
150E
195C
CENTRAL (HOST) POWER SOURCE
125
AC
130
100F

FIG.10

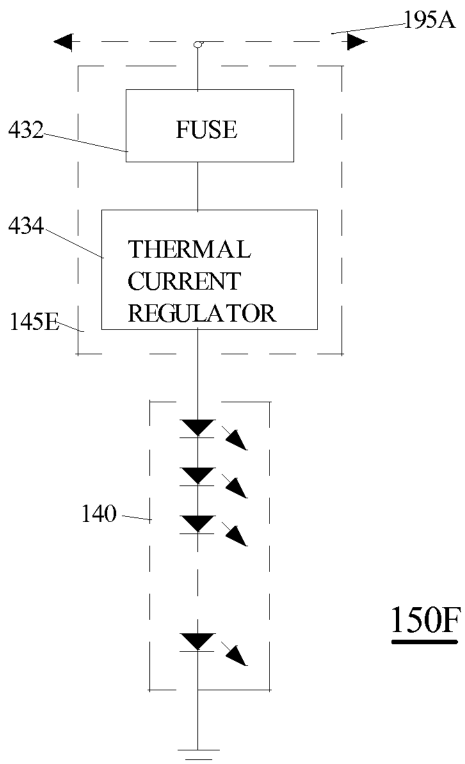


FIG. 11

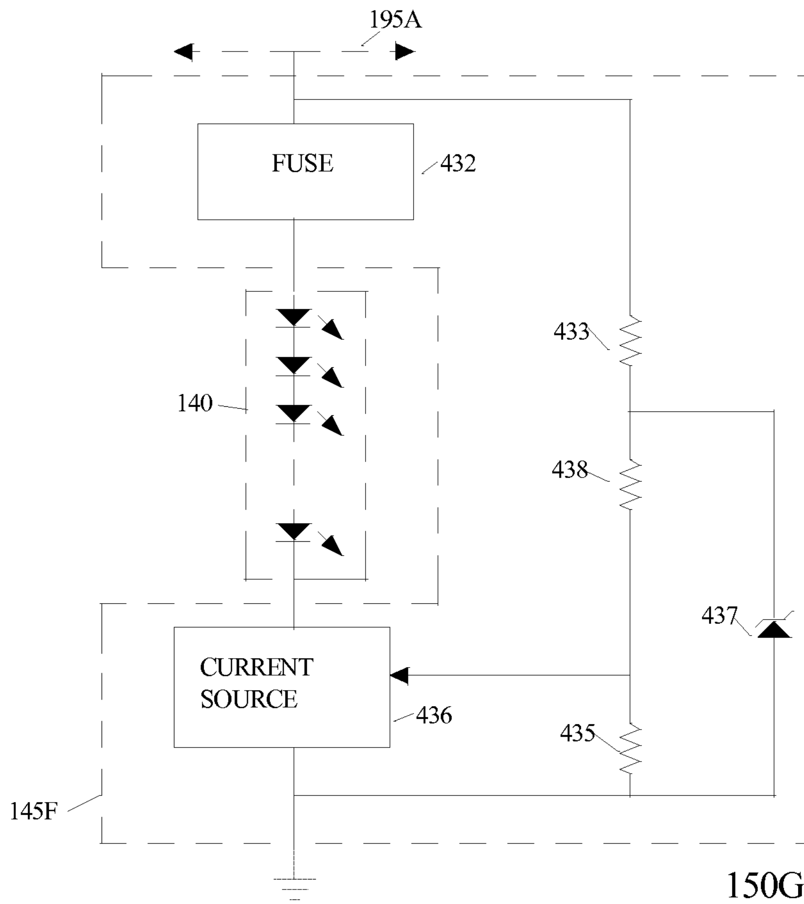
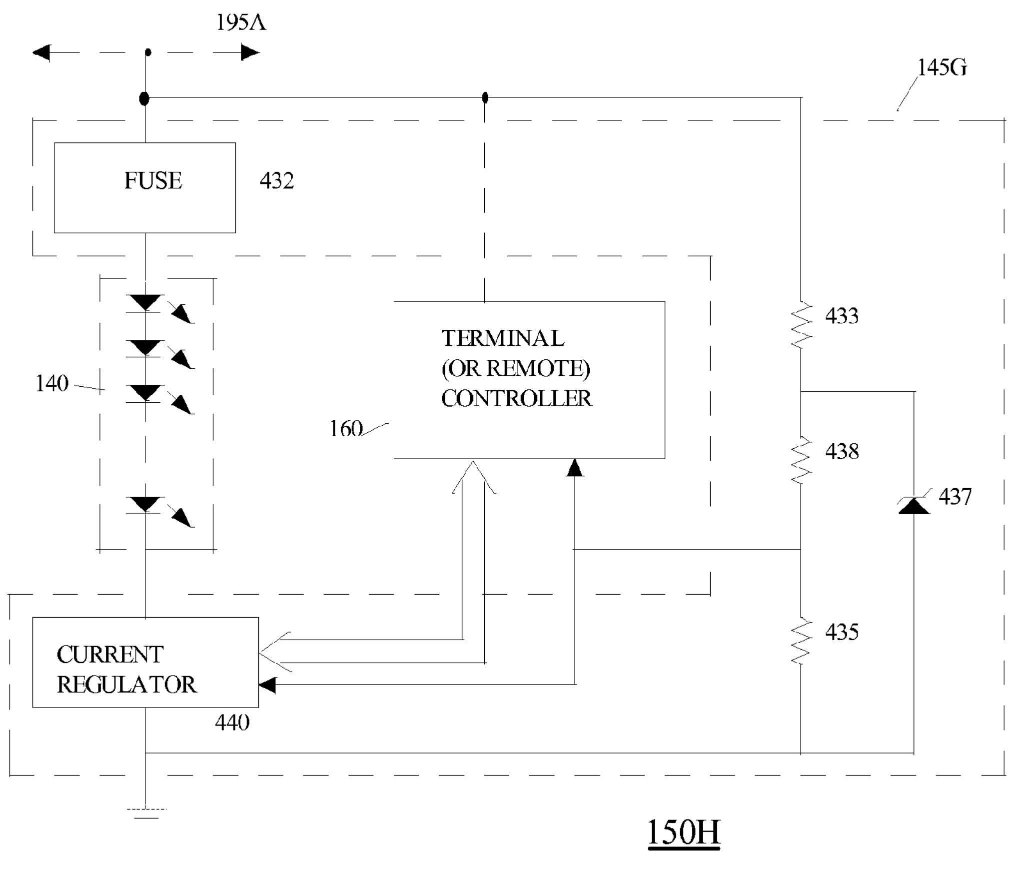

195A
FUSE
432
433
140
438
437
CURRENT SOURCE
436
435
145F
150G

FIG. 12



195A
145G
FUSE
432
140
TERMINAL
(OR REMOTE)
CONTROLLER
160
433
438
437
435
CURRENT
REGULATOR
440
150H

FIG. 13

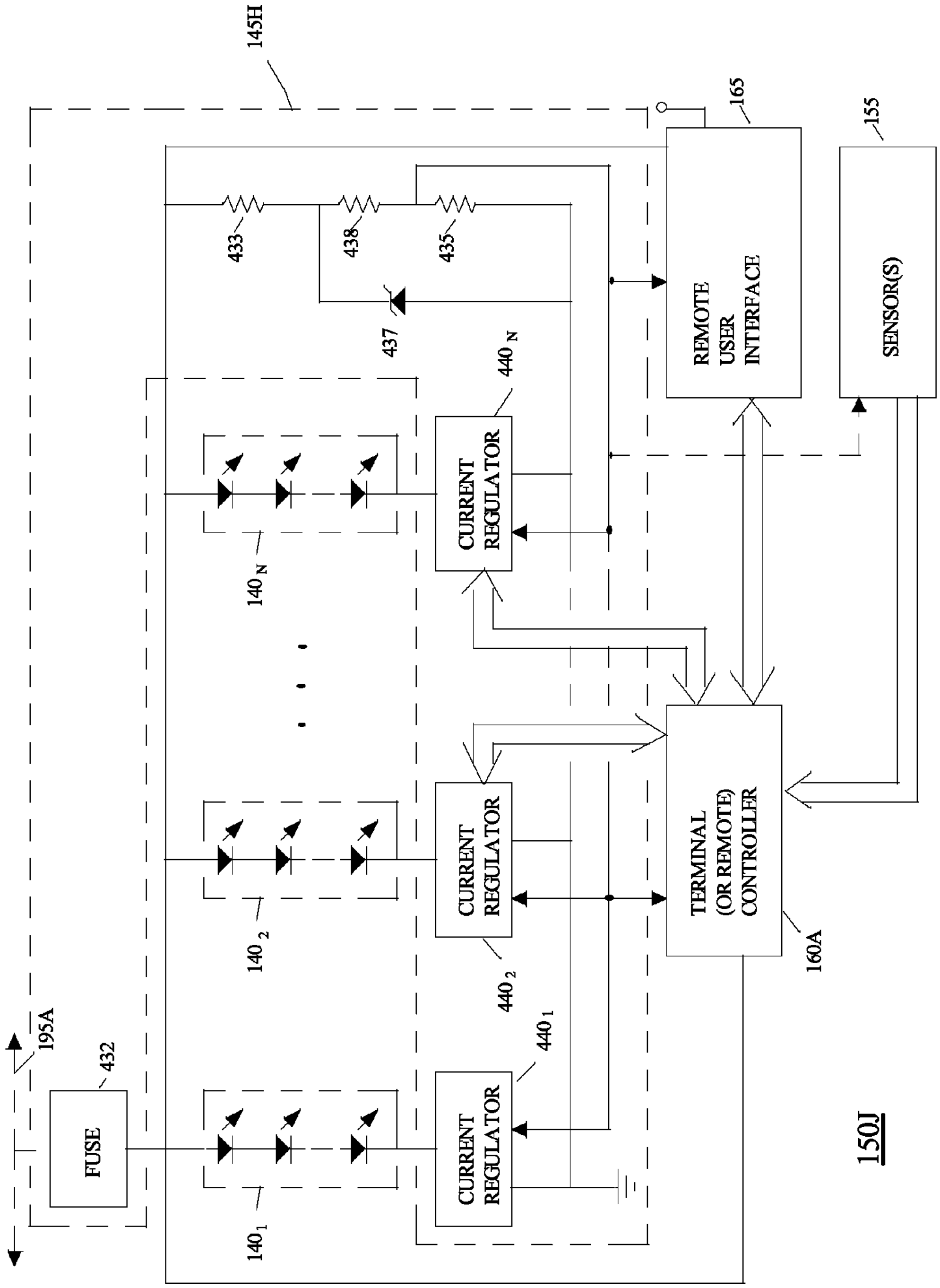
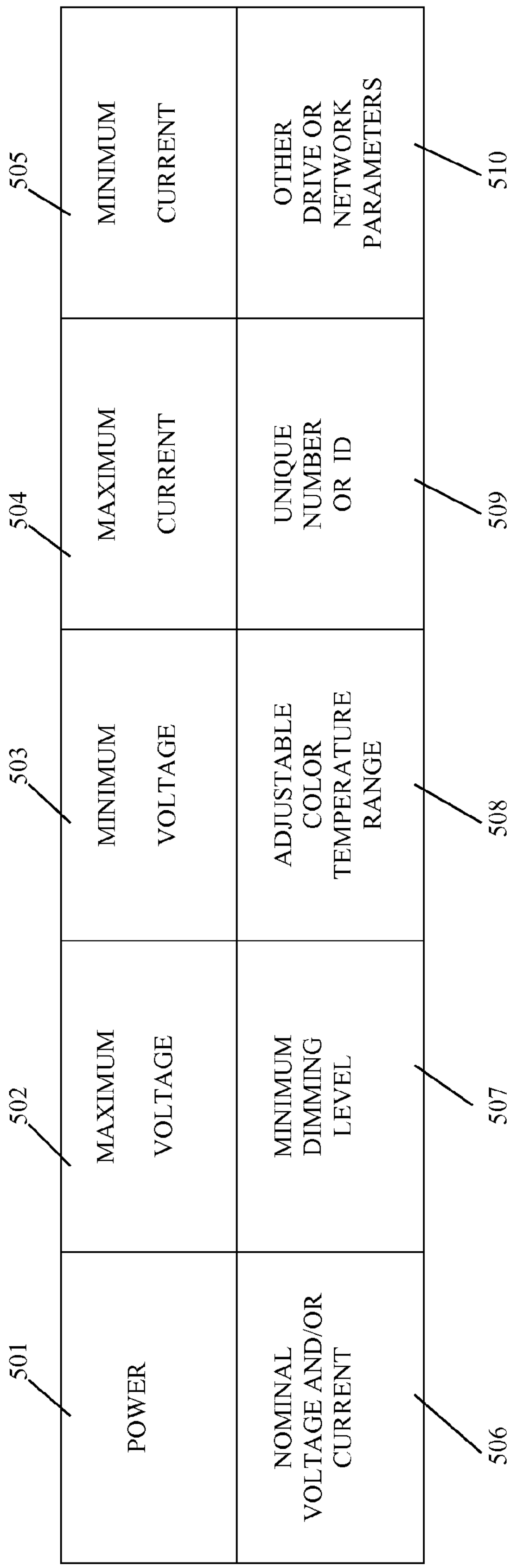

145H
165
155
433
438
435
437
REMOTE USER INTERFACE
SENSOR(S)
440_N
CURRENT REGULATOR
140_N
TERMINAL (OR REMOTE) CONTROLLER
140_2
440_2
160A
195A
432
FUSE
440_1
140_1
150J

FIG. 14


501
POWER
502
MAXIMUM VOLTAGE
503
MINIMUM VOLTAGE
504
MAXIMUM CURRENT
505
MINIMUM CURRENT
506
NOMINAL VOLTAGE AND/OR CURRENT
507
MINIMUM DIMMING LEVEL
508
ADJUSTABLE COLOR TEMPERATURE RANGE
509
UNIQUE NUMBER OR ID
510
OTHER DRIVE OR NETWORK PARAMETERS

170

FIG. 15

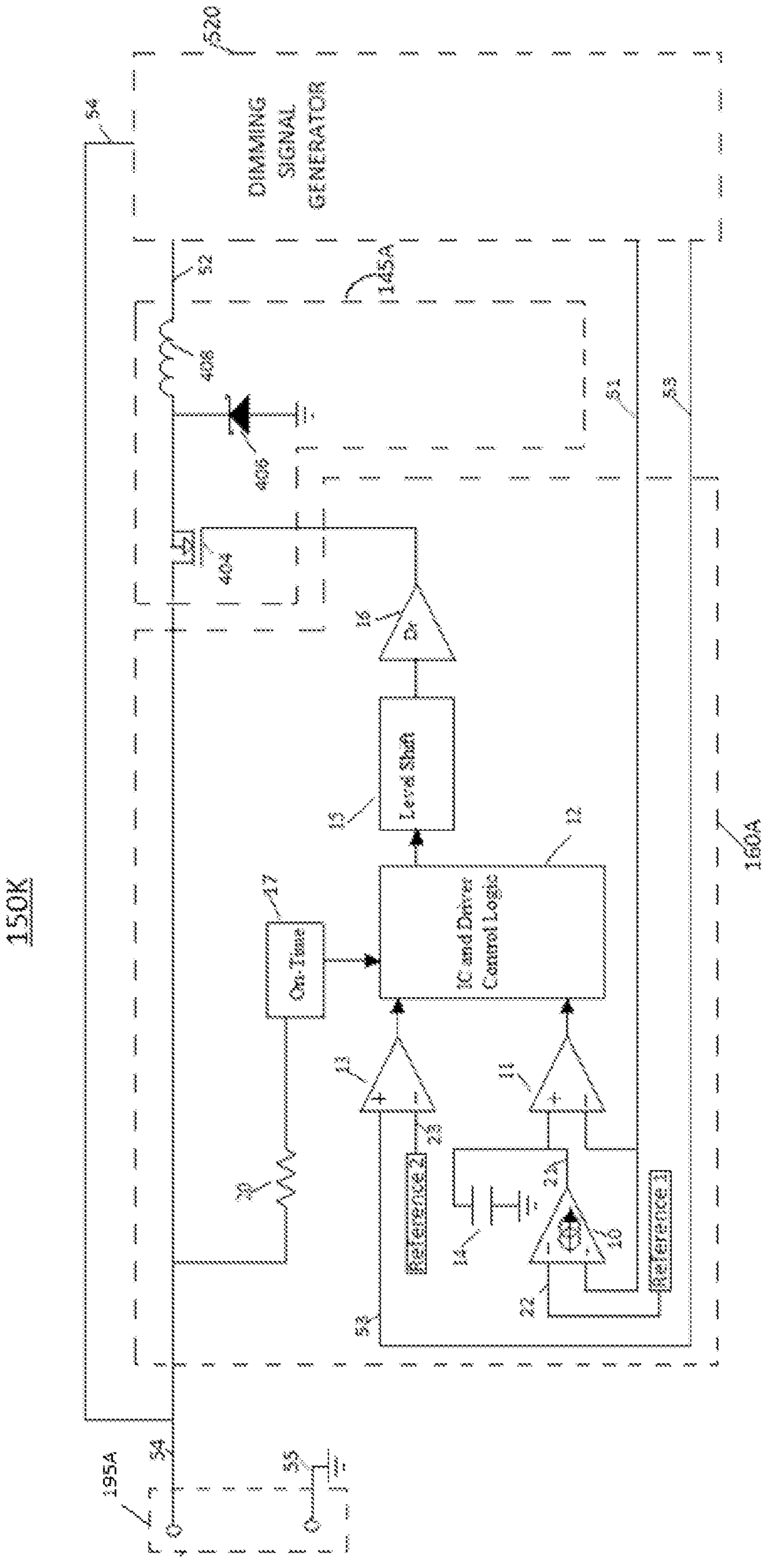

150K
DIMMING SIGNAL GENERATOR
520
54
52
145A
408
406
404
51
53
16
Dr
15
Level Shift
12
IC and Driver Control Logic
17
On-Time
13
11
23
Reference 2
30
14
24
10
22
Reference 1
160A
195A
55

FIG. 16

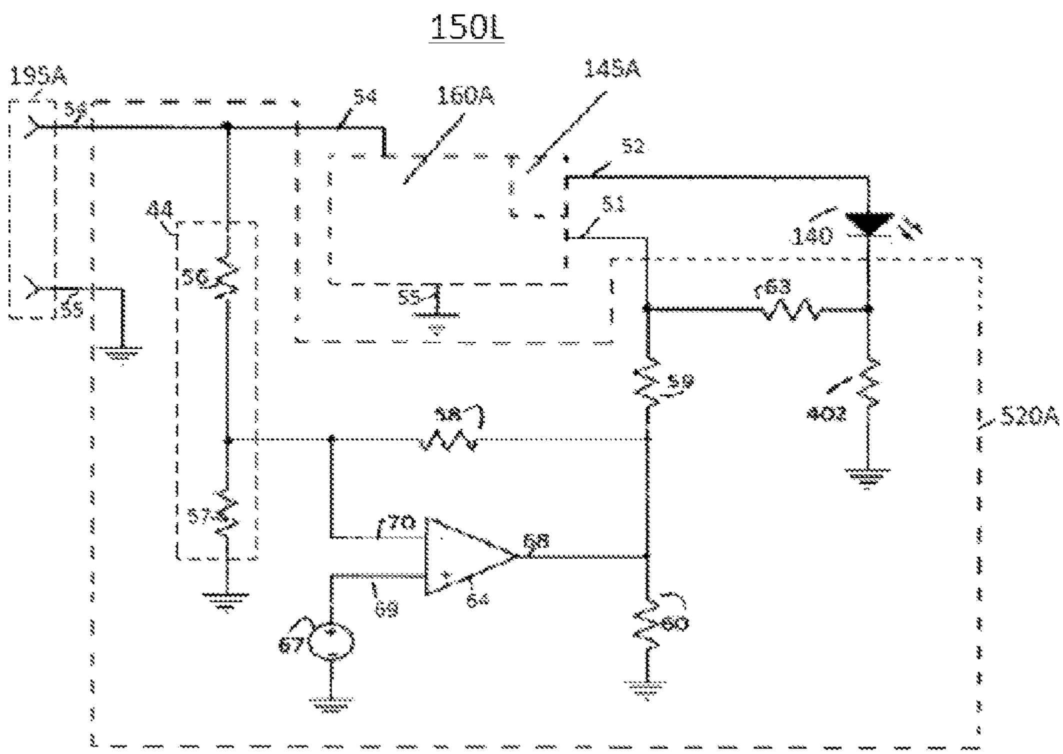

150L
195A
54
54
160A
145A
52
51
44
140
56
55
55
63
59
402
520A
58
57
70
68
69
64
67
60

FIG. 17

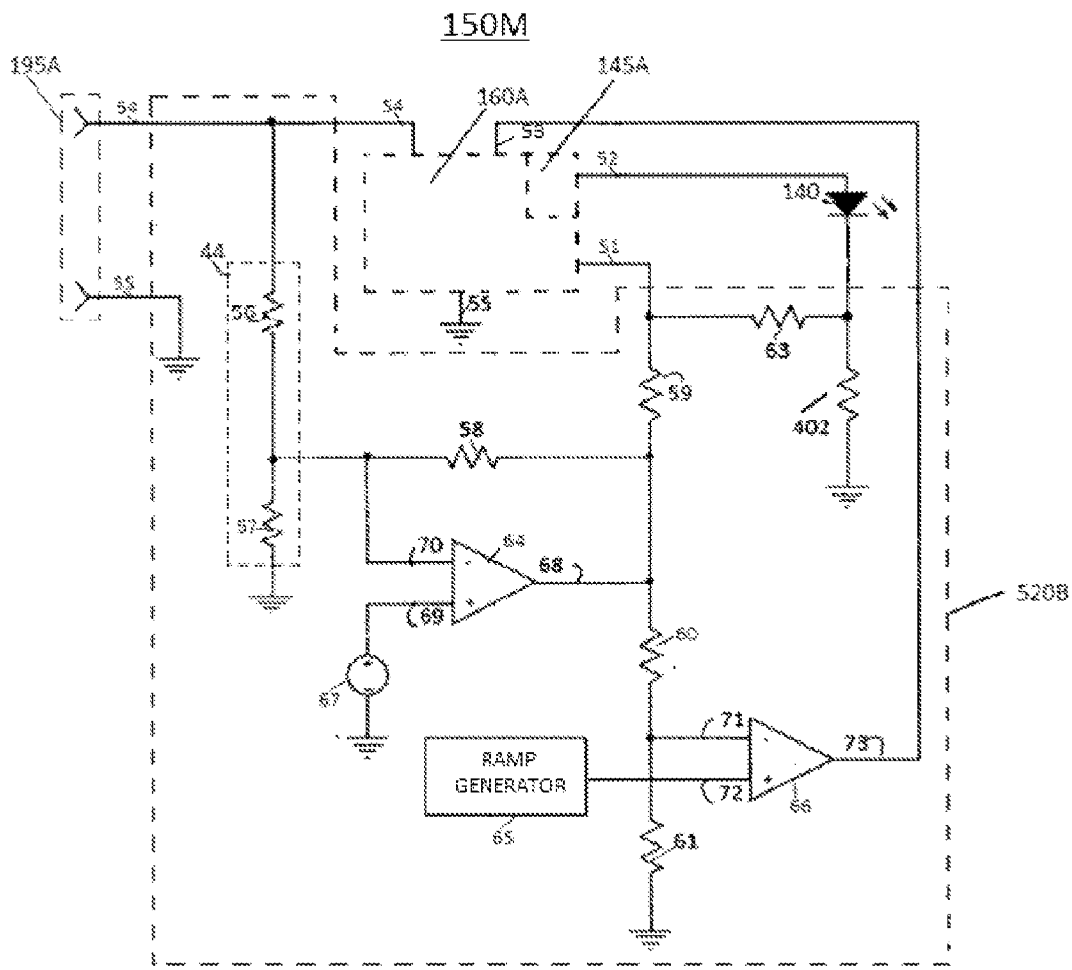

150M
195A
160A
145A
54
54
53
52
140
51
55
55
44
56
63
59
402
58
57
70
64
68
69
67
5208
60
71
73
RAMP GENERATOR
72
66
65
61

FIG. 18

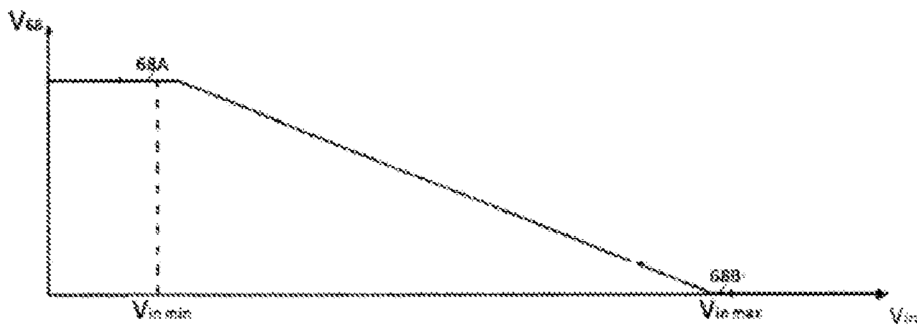


FIG. 19

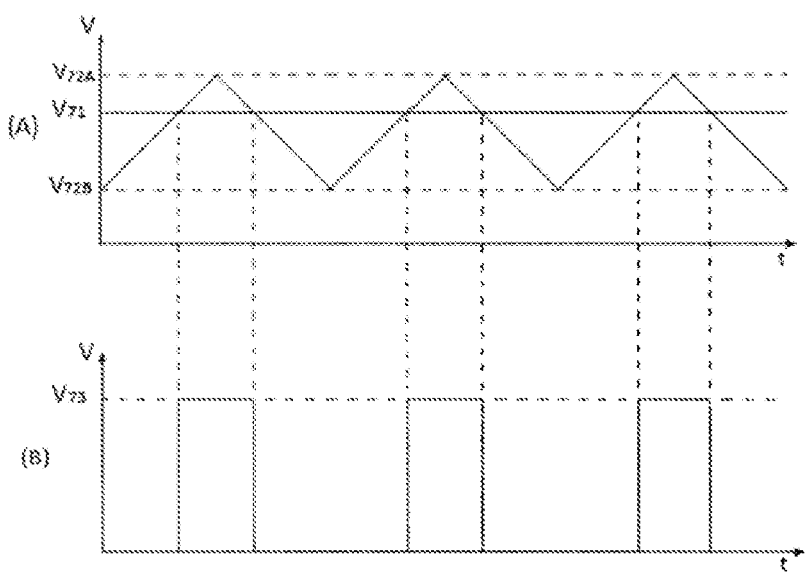


FIG. 20

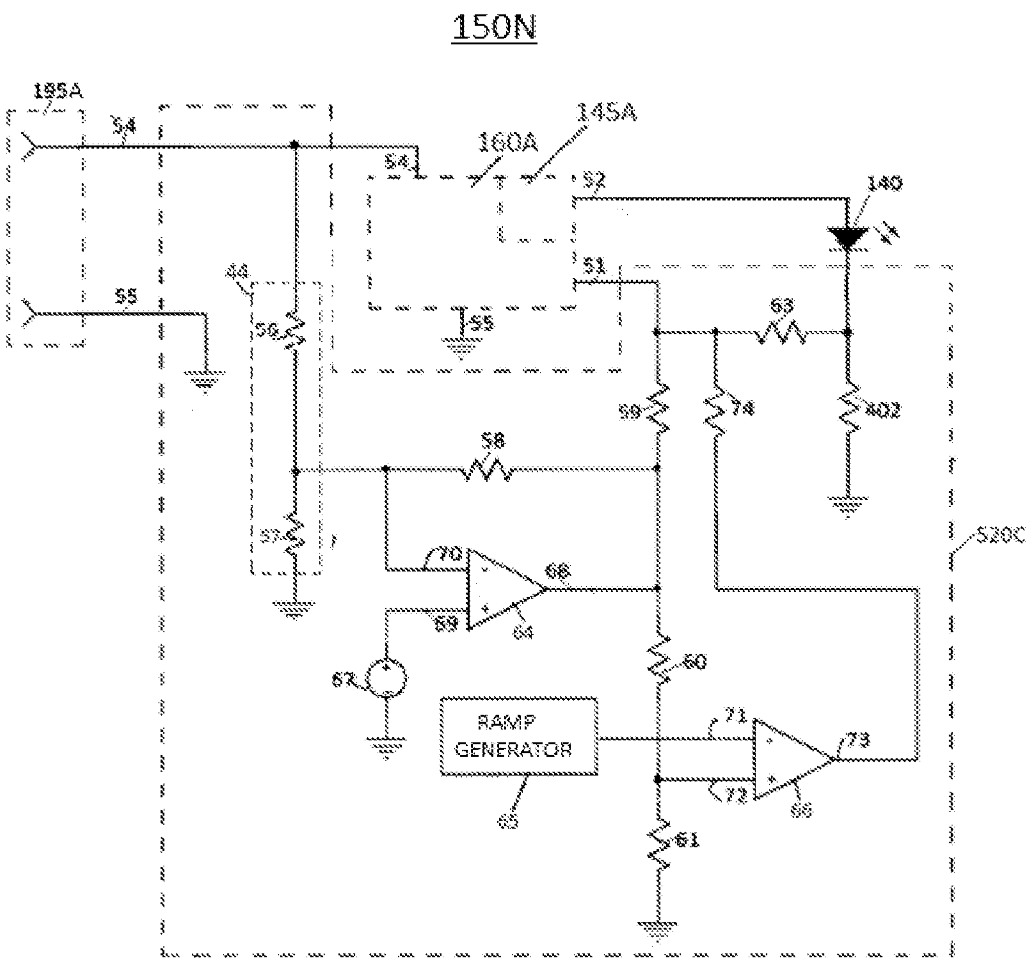

150N
195A
54
54
160A
145A
52
140
51
44
56
55
55
63
59
74
402
58
57
520C
70
68
69
64
67
60
RAMP GENERATOR
71
73
72
66
65
61

FIG. 21

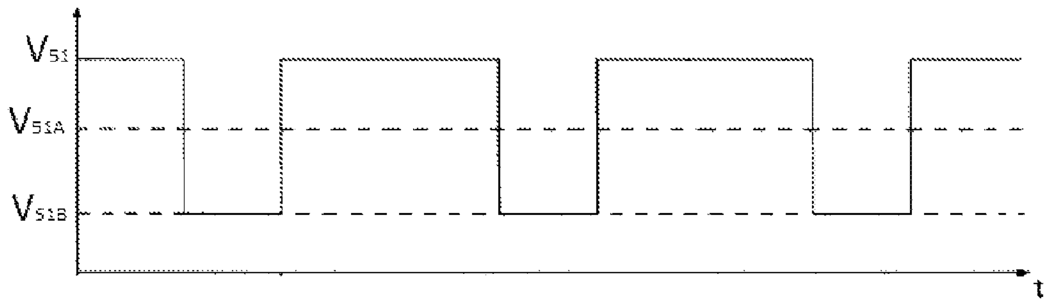


FIG. 22

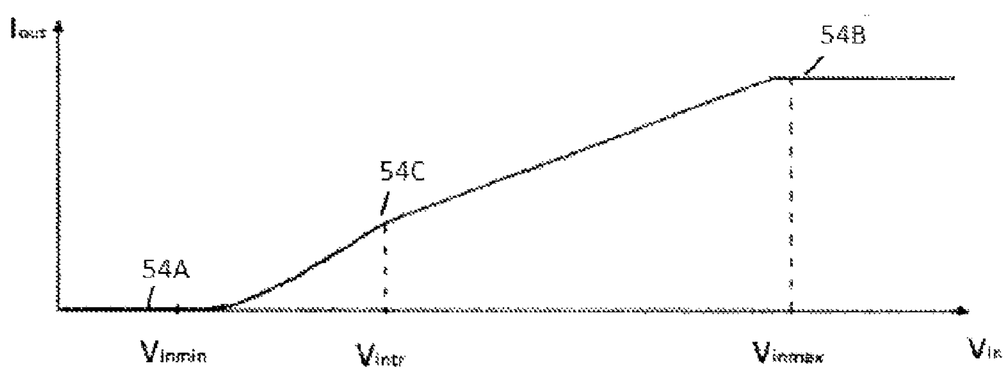


FIG. 23

150P

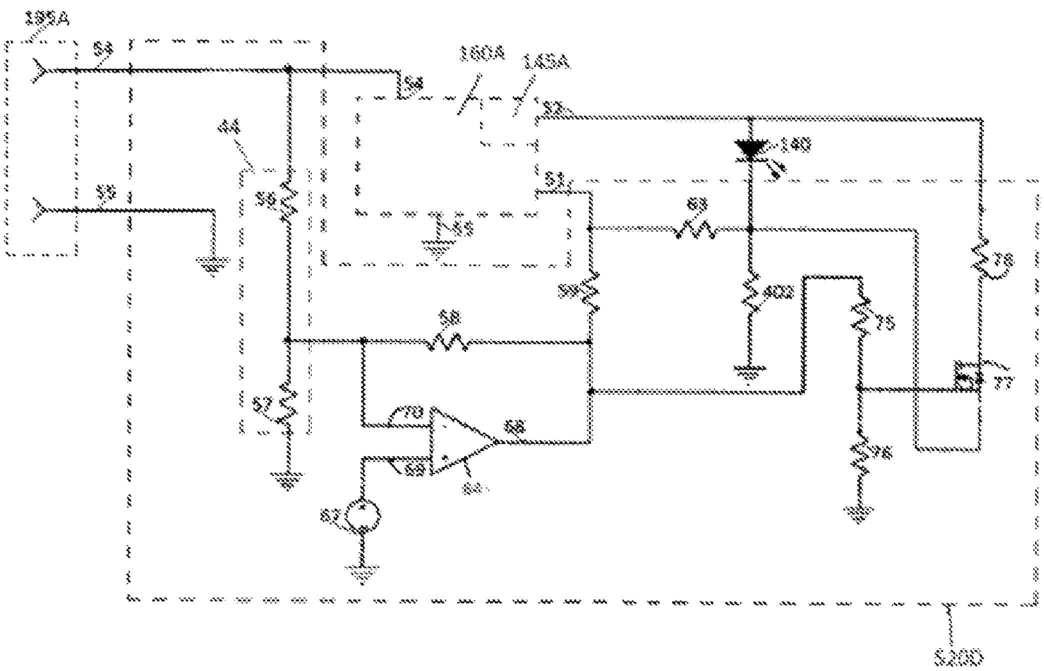

195A
54
55
44
56
57
58
59
160A
145A
52
51
53
140
63
400
75
76
77
78
70
68
69
64
62
520D

FIG. 24

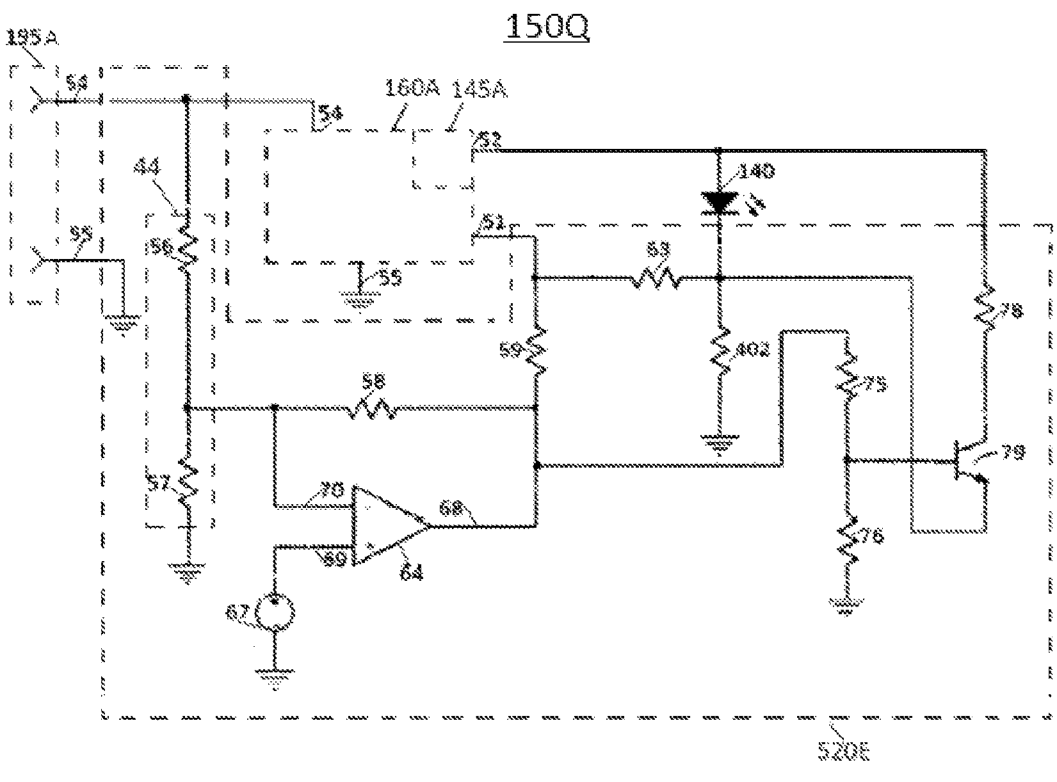

150Q
195A
54
54
160A
145A
52
140
44
55
51
56
53
55
78
59
402
75
58
79
57
70
68
69
64
76
62
520E

FIG. 25

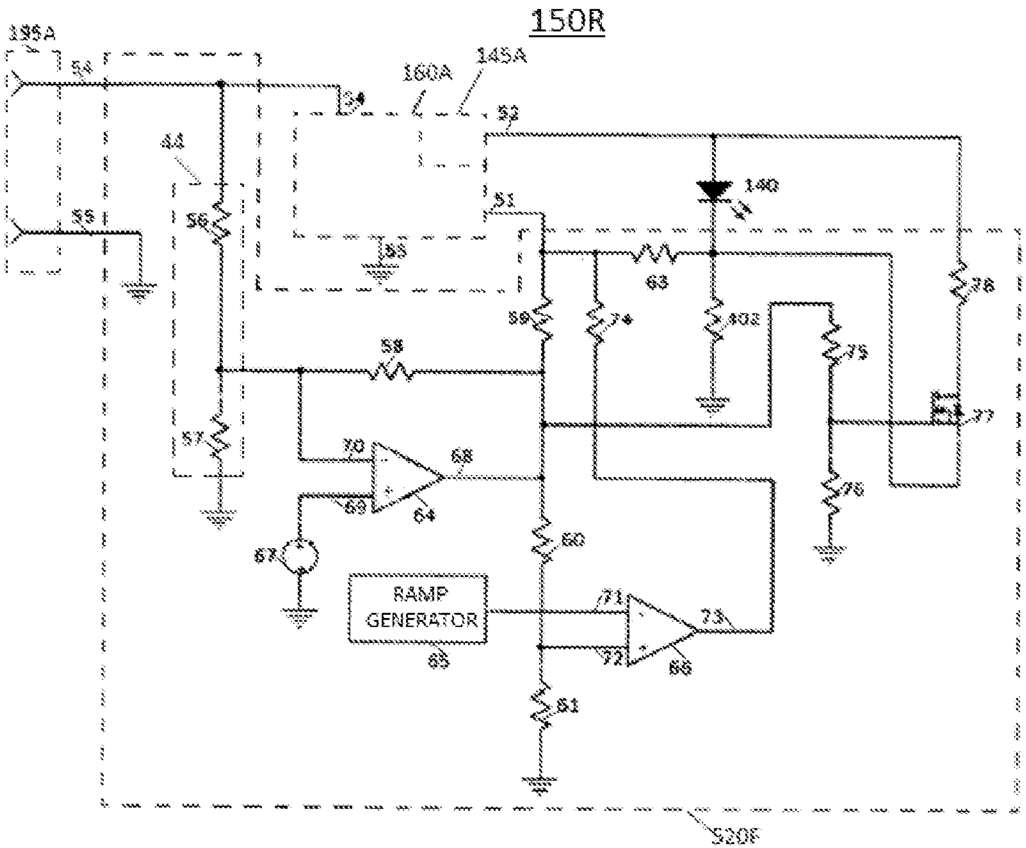

150R
195A
54
55
44
56
57
34
160A
145A
52
51
53
140
63
59
74
402
58
75
78
77
70
68
69
64
67
76
60
RAMP GENERATOR
65
71
72
73
66
61
520F

FIG. 26

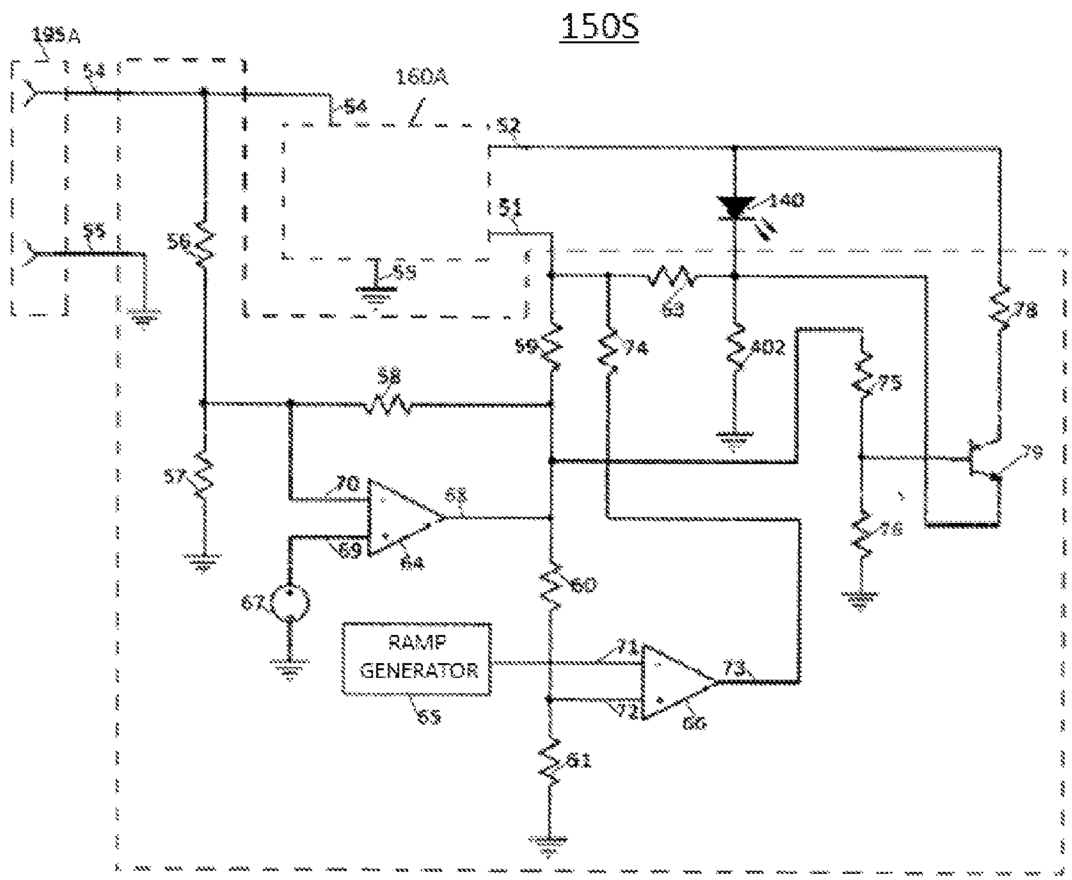
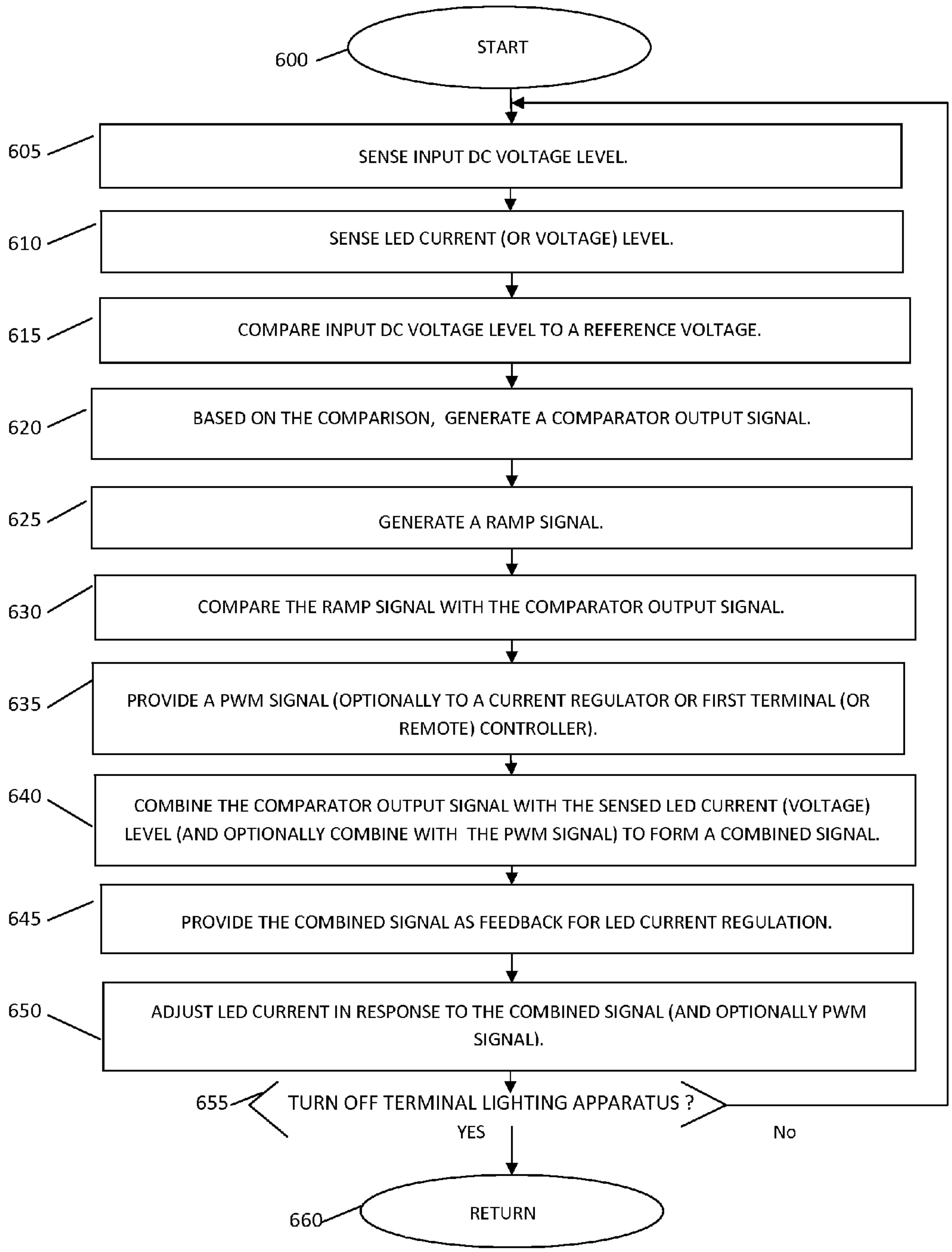

150S
195A
54
160A
52
140
51
55
56
59
74
63
402
78
58
75
57
70
68
79
69
64
76
67
60
RAMP GENERATOR
71
73
72
66
61

FIG.27



START
600
605
SENSE INPUT DC VOLTAGE LEVEL.
610
SENSE LED CURRENT (OR VOLTAGE) LEVEL.
615
COMPARE INPUT DC VOLTAGE LEVEL TO A REFERENCE VOLTAGE.
620
BASED ON THE COMPARISON, GENERATE A COMPARATOR OUTPUT SIGNAL.
625
GENERATE A RAMP SIGNAL.
630
COMPARE THE RAMP SIGNAL WITH THE COMPARATOR OUTPUT SIGNAL.
635
PROVIDE A PWM SIGNAL (OPTIONALLY TO A CURRENT REGULATOR OR FIRST TERMINAL (OR REMOTE) CONTROLLER).
640
COMBINE THE COMPARATOR OUTPUT SIGNAL WITH THE SENSED LED CURRENT (VOLTAGE) LEVEL (AND OPTIONALLY COMBINE WITH THE PWM SIGNAL) TO FORM A COMBINED SIGNAL.
645
PROVIDE THE COMBINED SIGNAL AS FEEDBACK FOR LED CURRENT REGULATION.
650
ADJUST LED CURRENT IN RESPONSE TO THE COMBINED SIGNAL (AND OPTIONALLY PWM SIGNAL).
655
TURN OFF TERMINAL LIGHTING APPARATUS ?
YES
No
660
RETURN

FIG. 28

APPARATUS AND METHOD FOR DIMMING SIGNAL GENERATION FOR A DISTRIBUTED SOLID STATE LIGHTING SYSTEM

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is continuation-in-part of and claims priority to U.S. patent application Ser. No. 13/664,068, filed Oct. 30, 2012, inventors Vladimir Korobov et al., entitled "Dimmable Solid State Lighting System, Apparatus and Method, with Distributed Control and Intelligent Remote Control", which is a conversion of and claims priority to U.S. Provisional Patent Application Ser. No. 61/606,837, filed Mar. 5, 2012, inventors Vladimir Korobov et al., entitled "A Power Control Unit for Power Supply to Driverless LED Lighting Apparatuses", which are commonly assigned herewith, the entire contents of which are incorporated herein by reference with the same full force and effect as if set forth in their entireties herein, and with priority claimed for all commonly disclosed subject matter.

FIELD OF THE INVENTION

The present invention in general is related to providing power through a centralized host power source to a plurality of distributed solid state lighting devices, such as bulbs and luminaires having light emitting diodes ("LEDs"), with dimming capabilities.

BACKGROUND OF THE INVENTION

Electrical lighting devices of many kinds, shapes and operational principles and capabilities, have gone through various generations of development since Edison's first incandescent electric light bulb. Today it is commonplace to find incandescent, Halogen and compact fluorescent light ("CFL") bulbs of all forms and shapes, as well as the beginning of a more modern kind of an electric lighting device that is based on light emitting diodes (LEDs). Such modern electric lighting devices can be found, for example, in the form of LED bulbs, LED luminaires, and the like. While the initial cost of such LED electric lighting devices may be higher than some of the other existing lighting solution, these costs may be offset due to the much longer lifetime of LED electric lighting devices and their significantly lower energy consumption costs. In addition, LED-based lighting generally provides better color rendering than CFL bulbs, i.e., a better quality of light, and are more environmentally friendly, both having many recyclable components and lacking the hazardous disposal issues of CFL bulbs.

Prior art LED bulbs and systems, however, tend to be overly complicated and typically incompatible with existing dimmer switches. Some require control methods that are complex, some are difficult to design and implement, and others require many electronic components. A large number of components results in an increased cost and reduced reliability. Many LED drivers utilize a current mode regulator with a ramp compensation in a pulse width modulation ("PWM") circuit. Other attempts provide solutions outside the original power converter stages, adding additional feedback and other circuits, rendering the LED driver even larger and more complicated.

For example, each individual, typical prior art LED bulb includes, in addition to the LEDs themselves, co-located LED driver circuitry comprising an AC/DC rectifier, a DC/DC converter, a current source, complicated circuitry for analog and PWM dimming, an additional dummy load for compatibility with existing triac-type dimmer switches, and additional feedback circuitry. A typical dummy load and special circuitry is required to support stable operation of a dimmer switch by providing a load to the dimmer during turn on, typically at a frequency of 60 Hz or 120 Hz, and reduces energy conversion efficiency. The significant gap between the high voltages of an input AC voltage and the lower DC voltages required for LEDs needs complex power conversion circuitry which may have as many as forty to seventy components, for example, with additional 10%-15% power losses from the conversion. Also for example, a dimmable LED driver may easily have 30% more circuitry than a nondimmable LED driver, and requires considerably more engineering resources to develop. In addition, a typical triac dimmer presents a comparatively poor interface to an AC line for solid state lighting, corrupting the power factor, introducing additional, nonfundamental harmonics, creating electromagnetic interference ("EMI") and audio noise problems, and increasing the input RMS current, further requiring corresponding increases in the value of service circuit breakers.

As a consequence, a need remains for a comparatively lower cost solution to provide LED-based lighting, using an apparatus, method and system suitable for replacing the problematic triac dimmer switches and other legacy wall-mounted switches, while simultaneously allowing the use of LED bulbs and luminaires which either utilize new interface standards or are compatible with existing or legacy interface standards, such as typical Edison-based sockets and interfaces, e.g., E12, E14, E26, E27, or GU-10 lighting standards. Such an apparatus, method and system should provide the capability for dimmable LED-based lighting, including remotely controlled dimming and color control, using LED bulbs and luminaires having comparatively few components, allowing lower cost manufacturing and corresponding savings to the consumer. Such an apparatus, method and system should provide comparative ease of use for a consumer, both for installation and bulb replacement.

Such an apparatus, method and system should also provide a wide range of dimming capability (i.e., depth of dimming), and be comparatively simple to implement using comparatively low cost components. Dimming in such lighting system could be executed, for example, by analog or pulse width modulation ("PWM") light regulation, should be capable of use with different types and qualities of LED bulbs, generally should be free of any significant flicker or other stroboscopic effects, and further should operate without causing electromagnetic interference. Such dimming should also be compatible with typical, widely-used interfaces or controllers. A need remains for an accurate dimming apparatus which provides a considerable depth of dimming, without complicated digital or analog controllers.

SUMMARY OF THE INVENTION

The exemplary embodiments of the present invention provide numerous advantages. Exemplary embodiments provide a comparatively lower cost solution to provide LED-based lighting. Various exemplary or representative apparatuses, methods and systems are disclosed which are suitable for replacing the problematic triac dimmer switches and other legacy wall-mounted switches. Various exemplary or representative apparatuses, methods and systems are disclosed which further provide for the use of LED bulbs and luminaires which either utilize new interface standards or are compatible with existing or legacy interface standards, such as typical Edison-based sockets and other standard interfaces mentioned above and below. Various exemplary embodiments provide the capability for dimmable LED-based lighting, including remotely controlled dimming and color control, using LED bulbs and luminaires having comparatively few components, allowing lower cost manufacturing and corresponding savings to the consumer. In addition, various exemplary or representative apparatuses, methods and systems are disclosed which provide comparative ease of use for a consumer, both for installation and bulb replacement.

Exemplary methods and apparatuses for a distributed solid-state lighting system are disclosed. An exemplary dimming signal generator apparatus includes an operational amplifier to receive a DC input voltage having the output inversely proportional to the input DC voltage and coupled with the current sense feedback input of the LED current source; a ramp generator, a current comparator to generate a PWM signal applied either to current sense feedback input or a dedicated PWM input of the current source in addition to the analog dimming signal to form a combined deep dimming regulation at low LED currents. To equalize currents in the different LED bulbs the transfer characteristic of input DC voltage to the LED current is formatted with flat regions allowing LED current to stay constant when input DC voltage is changing. LEDs may be bypassed with current sharing parallel networks to increase the regulation current above noise threshold and improve stability with no flickering during dimming.

An exemplary or representative distributed solid-state lighting system is disclosed, which comprises a central power source coupleable to an AC input power source, and one or more terminal lighting apparatuses coupled to and spaced apart from the central power source. An exemplary or representative central power source comprises: an AC/DC rectifier coupled to a DC/DC converter to convert the AC input power to a first DC voltage level; a central user interface to receive user input for a selected brightness level; and a central controller coupled to the DC/DC converter, the central controller to provide a first control signal to the DC/DC converter in response to the user input to provide a second DC voltage level corresponding to the selected brightness level.

In an exemplary or representative embodiment, each terminal lighting apparatus may comprise: a plurality of light emitting diodes; a current source or regulator coupled to the plurality of light emitting diodes; and a terminal controller coupled to the current source or regulator and, in response to the second DC voltage level, to provide a second control signal to the current source or regulator to provide a selected current level of the plurality of light emitting diodes corresponding to the selected brightness level.

Another exemplary or representative distributed solid-state lighting system is disclosed, comprising: a central power source coupleable to an AC input power source, the central power source to provide a selected DC output voltage level corresponding to a user selected brightness level; and one or more terminal lighting apparatuses coupled to and spaced apart from the central power source, each terminal lighting apparatus comprising: a plurality of light emitting diodes; and a current source or regulator coupled to the plurality of light emitting diodes.

Yet another exemplary or representative distributed solid-state lighting system is disclosed, comprising: one or more terminal lighting apparatuses, each terminal lighting apparatus comprising a plurality of light emitting diodes coupled to a current source or regulator; and a central power source coupleable to an AC input power source and coupled to and spaced apart from the one or more terminal lighting apparatuses, the central power source to provide a selected DC output voltage level to the one or more terminal lighting apparatuses. In various exemplary or representative embodiments, the selected DC output voltage level corresponds to a user selected brightness level.

In various exemplary or representative embodiments, for example, the central controller is to determine the second DC voltage level Vout as:

$$V\text{out}=\rho\Delta V\text{outmax}+V\text{outmin}$$

in which "ρ" is a user selectable brightness level and corresponds to

$$\rho=\frac{I_{out}}{I_{outn}},$$

ΔVoutmax=Voutmax−Voutmin, Iout is the selected current level of the plurality of light emitting diodes for one or more terminal lighting apparatuses, Ioutn is the nominal current level of the plurality of light emitting diodes for one or more terminal lighting apparatuses, Voutmax=Vinmax in which Vinmax is the maximum input voltage to the one or more terminal lighting apparatuses, and Voutmin=Vinmin in which Vinmin is the minimum input voltage to the one or more terminal lighting apparatuses.

Also in various exemplary or representative embodiments, for example, the terminal controller is to determine the LED current Iout as proportional to the input voltage Vin, in which Iout is the selected current level of the plurality of light emitting diodes for the terminal lighting apparatus having the terminal controller, and Vin the sensed input voltage of the terminal lighting apparatus. Such proportionality may be linear or nonlinear, as described in greater detail below. In various exemplary or representative embodiments, the terminal controller is to determine the LED current Iout as linearly proportional to the input voltage Vin, namely, Iout=μVin, in which t is a linear transfer function, Iout is the selected current level of the plurality of light emitting diodes for the terminal lighting apparatus having the terminal controller, and Vin the sensed input voltage of the terminal lighting apparatus.

In another exemplary or representative embodiment, also for example, the terminal controller is to determine the LED current Iout as linearly proportional to the input voltage Vin, namely, Iout=μVin, where μ is a linear transfer function,

$$\mu=\frac{(V_{in}-V_{inmin})I_{outn}}{\Delta V_{inmax}V_{in}},$$

in which ΔVinmax=Vinmax−Vinmin, Iout is the selected current level of the plurality of light emitting diodes for one or more terminal lighting apparatuses, Ioutn is the nominal current level of the plurality of light emitting diodes for one or more terminal lighting apparatuses, Vinmax is the maximum input voltage to the one or more terminal lighting apparatuses, Vinmin is the minimum input voltage to the one or more terminal lighting apparatuses, and Vin the sensed input voltage of the terminal lighting apparatus.

In a selected exemplary or representative embodiment, the central user interface further comprises a scanner to scan a plurality of machine-readable encoded fields. Also for example, the plurality of machine-readable encoded fields may comprise data encoding a plurality of operational parameters for a given terminal lighting apparatus, such as any of the various Vinmax, Vinmin, and ΔVinmax parameters mentioned above. In various exemplary or representative embodiments, the central controller further is to utilize the plurality of operational parameters to determine the second DC voltage level provided to the one or more terminal lighting apparatuses.

In various exemplary or representative embodiments, the plurality of operational parameters comprise at least two operational parameters selected from the group consisting of: a maximum input voltage, a minimum input voltage, a maximum input current, a minimum input current, a nominal power level, a voltage level at a nominal current level, a minimum dimming level, an adjustable color temperature range, a unique identifier, and combinations thereof.

In an exemplary or representative embodiment, a current source or regulator comprises: a fuse; and a thermal current regulator.

In another exemplary or representative embodiment, a current source or regulator comprises a converter selected from the group consisting of: a buck converter; a boost converter; a buck-boost converter; a flyback converter; a sepic converter; and combinations thereof.

In yet another exemplary or representative embodiment, a current source or regulator comprises: a fuse; a current source; and a voltage divider to provide an operating voltage to the current source.

In an exemplary or representative embodiment, a terminal lighting apparatus may further comprise: a terminal controller coupled to the current source or regulator and, in response to the second DC voltage level, provides a second control signal to the current source or regulator to provide a selected current level of the plurality of light emitting diodes corresponding to the selected brightness level.

In another exemplary or representative embodiment, the plurality of light emitting diodes further comprise a plurality of series-connected light emitting diodes forming a plurality of channels of light emitting diodes, each channel corresponding to a different emission color of light emitting diodes, and wherein each terminal lighting apparatus further comprises: a remote user interface to receive user input for a selected emission color or color temperature of a plurality of emission colors and color temperatures.

In yet another exemplary or representative embodiment, a system may further comprise: an inverter to convert the second DC voltage level to an AC voltage level having a frequency in the range of about 500 Hz to 90 kHz. For such an exemplary or representative embodiment, a current source or regulator may comprise: a transformer; and a rectifier.

As another exemplary or representative embodiment, the plurality of light emitting diodes may be coupled in series to form a series-connected current path and the current source or regulator may comprise: a transformer; a rectifier; and a plurality of switches coupled to the plurality of light emitting diodes to switch a selected light emitting diode in or out of the series-connected current path.

Exemplary or representative methods of providing power to a spatially-distributed plurality of terminal lighting apparatuses, each comprising a plurality of light emitting diodes, are also disclosed. An exemplary or representative method comprises: receiving a selected brightness level through a user interface; using a central controller, determining a dimming level "ρ"; using a central controller, determining an output voltage or output current level; rectifying an input AC voltage (current) and providing corresponding DC output voltage and current levels; and monitoring output voltage or output current levels and providing a first feedback signal to maintain the output voltage or output current level at the determined level.

In an exemplary or representative method embodiment, the output voltage is calculated as Vout=ρΔVoutmax+Voutmin, in which "ρ" is a user selectable brightness level and corresponds to

$$\rho = \frac{I_{out}}{I_{outn}},$$

ΔVoutmax=Voutmax−Voutmin, Iout is the selected current level of the plurality of light emitting diodes for one or more terminal lighting apparatuses, Ioutn is the nominal current level of the plurality of light emitting diodes for one or more terminal lighting apparatuses, Voutmax=Vinmax in which Vinmax is the maximum input voltage to the one or more terminal lighting apparatuses, and Voutmin=Vinmin in which Vinmin is the minimum input voltage to the one or more terminal lighting apparatuses.

An exemplary or representative method may further comprise: using an input scanner, receiving a plurality of operational parameters corresponding to a selected terminal LED lighting apparatus. For example, the plurality of operational parameters may be encoded in a UPC-barcode or QR code format.

An exemplary or representative method may further comprise: receiving an input voltage; using a terminal controller and using the received input voltage level, calculating or determining an LED current level Iout for the plurality of light emitting diodes of a selected terminal lighting apparatus of the plurality of terminal lighting apparatuses; setting the LED current level to the value of Iout; and monitoring the LED current level and providing a second feedback signal to maintain the LED current level at the determined level Iout.

In another exemplary or representative embodiment, a method is disclosed for dimming a brightness level of a terminal lighting apparatus, comprising a plurality of light emitting diodes, with the exemplary or representative method comprising: receiving an input voltage at the terminal lighting apparatus; using a terminal controller and using the received input voltage level, calculating or determining an LED current level Iout; setting the LED current level to the value of Iout; and monitoring the LED current level and providing a feedback signal to maintain the LED current level at the determined level Iout.

For example, the LED current level Iout may be calculated as Iout=μVin, where μ is a selected transfer function, Iout is the selected current level of the plurality of light emitting diodes, and Vin the sensed input voltage of the selected terminal lighting apparatus, as mentioned above. Also for example, μ may be a linear transfer function, such as

$$\mu = \frac{(V_{in} - V_{inmin})I_{outn}}{\Delta V_{inmax} V_{in}},$$

or μ may be a nonlinear transfer function, as mentioned above and as further described below.

In another exemplary or representative embodiment, the LED current level Iout is determined using the sensed value of Vin as an index into a look up table stored in memory.

An exemplary or representative kit for a distributed solid-state lighting system is also disclosed. For example, such a kit may comprise: a central power source and one or more terminal lighting apparatuses. Such a central power source may comprise: an AC/DC rectifier coupled to a DC/DC converter to convert an AC input power to a first DC voltage level; a central user interface to receive user input for a selected brightness level; and a central controller coupled to the DC/DC converter, the central controller to provide a first control signal to the DC/DC converter in response to the user input to provide a second DC voltage level corresponding to the selected brightness level. Each terminal lighting apparatus may comprise: a plurality of light emitting diodes; a current source or regulator coupled to the plurality of light emitting diodes; and a terminal controller coupled to the current source or regulator and, in response to the second DC voltage level, to provide a second control signal to the current source or regulator to provide a selected current level of the plurality of light emitting diodes corresponding to the selected brightness level.

In an exemplary or representative kit, for example, each terminal lighting apparatus is embodied as an LED bulb or luminary having an interface compatible with an interface standard selected from a group consisting of: an E12 lighting standard, an E14 lighting standard, an E26 lighting standard, an E27 lighting standard, a GU-10 lighting standard, and combinations thereof.

Another exemplary or representative embodiment provides a dimming signal generator coupleable to a controller or a current generator for a plurality of light emitting diodes (LEDs), the exemplary or representative dimming signal generator comprising: a first resistive voltage divider to sense an input DC voltage; a current sensor to sense a current level of the plurality of LEDs; a first operational amplifier coupled to the first resistive voltage divider, the first operational amplifier to compare the sensed input DC voltage to a reference voltage level, and to provide a comparator output signal; and a current path coupled to an output of the first operational amplifier to combine the comparator output signal with the sensed LED current level to provide a combined signal for current level feedback for control of the LED current level.

In an exemplary or representative embodiment, the dimming signal generator may further comprise: a ramp signal generator; and a second operational amplifier coupled to the ramp signal generator and to the output of the first operational amplifier, the second operational amplifier to provide a pulse width modulated signal. In an exemplary or representative embodiment, the second operational amplifier is further coupled to an input of the controller to provide the pulse width modulated signal directly to the controller for pulse width modulation of the LED current. In another exemplary or representative embodiment, the second operational amplifier is further coupled to the current path to combine the pulse width modulated signal into the combined signal.

In an exemplary or representative embodiment, the second operational amplifier may compare the ramp signal with the comparator output signal to generate the pulse width modulated signal.

In another exemplary or representative embodiment, the dimming signal generator may further comprise: a resistive network coupleable in parallel with the plurality of LEDs; a second resistive voltage divider coupled to the output of the first operational amplifier; and a switch coupled to the resistive network and to the second resistive voltage divider to divert current from the plurality of LEDs in response to the comparator output signal. For example, the switch may be a MOSFET or a bipolar transistor.

In an exemplary or representative embodiment of the dimming signal generator, the comparator output signal is inversely proportional to the sensed input DC voltage level. For example, when the combined signal is greater than the sensed LED current level, it will cause a decrease in the LED current level and provide dimming of the LEDs.

Another exemplary or representative embodiment provides a dimming signal generator coupleable to a controller or a current generator for a plurality of light emitting diodes (LEDs), the dimming signal generator comprising: a first resistive voltage divider to sense an input DC voltage; a current sensor to sense a current level of the plurality of LEDs; a first operational amplifier coupled to the first resistive voltage divider, the first operational amplifier to compare the sensed input DC voltage to a reference voltage level, and to provide a comparator output signal; a ramp signal generator; and a second operational amplifier coupled to the ramp signal generator and to the output of the first operational amplifier, the second operational amplifier to compare the ramp signal with the comparator output signal to generate a pulse width modulated signal; and a current path coupled to an output of the first operational amplifier to combine the comparator output signal with the sensed LED current level to provide a combined signal for current level feedback for control of the LED current level.

Another exemplary or representative embodiment provides a light emitting apparatus comprising: a plurality of light emitting diodes (LEDs); a current generator coupled to the plurality of LEDs; a controller coupled to the current generator; and a dimming signal generator coupled to the controller, the dimming signal generator to provide a combined signal for current level feedback for control of the LED current level.

Yet another exemplary or representative embodiment provides a method of providing brightness dimming of a plurality of light emitting diodes (LEDs), the method comprising: sensing an input DC voltage level; sensing an LED current level; using a first operational amplifier, comparing the input DC voltage level to a reference voltage and generating a comparator output signal; combining the comparator output signal with the sensed LED current level and pulse width modulation signal to form a combined signal; providing the combined signal as feedback for LED current regulation; and adjusting the LED current in response to the combined signal.

In an exemplary or representative embodiment, the method may further comprise: generating a ramp signal; using a second operational amplifier, generating a pulse width modulation signal. In an exemplary or representative embodiment, the method may further comprise providing the pulse width modulated signal directly to a controller for pulse width modulation of the LED current. In another exemplary or representative embodiment, the method may further comprise combining the pulse width modulated signal into the combined signal.

In an exemplary or representative embodiment, the step of generating the pulse width modulation signal may further comprise comparing the ramp signal with the comparator output signal. In another exemplary or representative embodiment, the step of generating the pulse width modulation signal may further comprise, using a switch, diverting current from the plurality of LEDs in response to the comparator output signal.

Numerous other advantages and features of the present invention will become readily apparent from the following detailed description of the invention and the embodiments thereof, from the claims and from the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

The objects, features and advantages of the present invention will be more readily appreciated upon reference to the following disclosure when considered in conjunction with the accompanying drawings, wherein like reference numerals are used to identify identical components in the various views, and wherein reference numerals with alphabetic characters are utilized to identify additional types, instantiations or variations of a selected component embodiment in the various views, in which:

FIG. **1** is a block diagram illustrating an exemplary or representative lighting system, an exemplary or representative central (host) power source, and a first exemplary or representative terminal LED lighting apparatus.

FIG. **2** is a flow diagram illustrating an exemplary or representative preoperational method for set up and exchange modes of an exemplary or representative lighting system and an exemplary or representative central (host) power source.

FIG. **3**, divided into FIGS. **3**A and **3**B, is a flow diagram illustrating an exemplary or representative method of operating an exemplary or representative lighting system, an exemplary or representative central (host) power source, and an exemplary or representative terminal LED lighting apparatus.

FIG. **4** is a graph illustrating exemplary or representative voltage and current waveforms for intelligent dimming using an exemplary or representative lighting system, an exemplary or representative central (host) power source, and an exemplary or representative terminal LED lighting apparatus.

FIG. **5** is a block and circuit diagram illustrating a second exemplary or representative terminal LED lighting apparatus for use in a comparatively low voltage DC system.

FIG. **6** is a block and circuit diagram illustrating a third exemplary or representative terminal LED lighting apparatus for use in a comparatively high voltage DC system.

FIG. **7** is a block diagram illustrating a second exemplary or representative system having both comparatively high and low DC levels.

FIG. **8** is a block and circuit diagram illustrating a fourth exemplary or representative terminal LED lighting apparatus for use in a comparatively high frequency system.

FIG. **9** is a block and circuit diagram illustrating a fifth exemplary or representative terminal LED lighting apparatus for use in a comparatively high frequency system.

FIG. **10** is a block and circuit diagram illustrating a sixth exemplary or representative terminal LED lighting apparatus for use in a comparatively high frequency system.

FIG. **11** is a block and circuit diagram illustrating a seventh exemplary or representative terminal LED lighting apparatus for a comparatively low voltage DC system.

FIG. **12** is a block and circuit diagram illustrating an eighth exemplary or representative terminal LED lighting apparatus for a comparatively low voltage DC system.

FIG. **13** is a block and circuit diagram illustrating a ninth exemplary or representative terminal LED lighting apparatus for a comparatively low voltage DC system.

FIG. **14** is a block and circuit diagram illustrating a tenth exemplary or representative terminal LED lighting apparatus for a comparatively low voltage DC system.

FIG. **15** is a diagram illustrating exemplary or representative machine-readable encoded fields, such as barcode fields or QR code fields, for use with an exemplary or representative apparatus, method and system.

FIG. **16** is a block and circuit diagram illustrating an eleventh exemplary or representative terminal LED lighting apparatus for use in a comparatively low voltage DC system with an exemplary or representative first terminal or remote controller and an exemplary or representative dimming signal generator.

FIG. **17** is a block and circuit diagram illustrating an exemplary or representative first dimming signal generator implemented using analog control.

FIG. **18** is a block and circuit diagram illustrating an exemplary or representative second dimming signal generator, implementing combined analog and PWM control.

FIG. **19** is a graphical diagram illustrating an output control voltage signal as a function of input voltage.

FIG. **20** is graphical diagram illustrating (a) a sawtooth waveform, and (b) a PWM signal.

FIG. **21** is a block and circuit diagram illustrating a third dimming signal generator having combined analog and PWM control, in which the PWM is summed with the analog control signal.

FIG. **22** illustrates an exemplary waveform of a PWM signal summed with the analog dimming signal.

FIG. **23** is a graphical diagram illustrating a regulation characteristic of the third dimming signal generator with combined analog and PWM dimming regulation.

FIG. **24** is a block and circuit diagram illustrating an exemplary or representative fourth dimming signal generator with analog dimming regulation and a resistive network controlled by a MOSFET.

FIG. **25** is a block and circuit diagram illustrating an exemplary or representative fifth dimming signal generator with analog dimming regulation and a resistive network controlled by a bipolar transistor.

FIG. **26** is a block and circuit diagram illustrating an exemplary or representative sixth dimming signal generator having combined analog and PWM control, in which the PWM is summed with the analog control signal, and a resistive network controlled by a MOSFET.

FIG. **27** is a block and circuit diagram illustrating an exemplary or representative seventh dimming signal generator having combined analog and PWM control, in which the PWM is summed with the analog control signal, and a resistive network controlled by a bipolar transistor.

FIG. **28** is a flow diagram illustrating a method of providing dimming regulation.

DETAILED DESCRIPTION OF REPRESENTATIVE EMBODIMENTS

While the present invention is susceptible of embodiment in many different forms, there are shown in the drawings and will be described herein in detail specific exemplary embodiments thereof, with the understanding that the present disclosure is to be considered as an exemplification of the principles of the invention and is not intended to limit the invention to the specific embodiments illustrated. In this respect, before explaining at least one embodiment consistent with the present invention in detail, it is to be understood that the invention is not limited in its application to the details of construction and to the arrangements of components set forth above and below, illustrated in the drawings, or as described in the examples. Methods and apparatuses consistent with the present invention are capable of other embodiments and of being practiced and carried out in various ways. Also, it is to be understood that the phraseology and terminology employed herein, as well as the abstract included below, are for the purposes of description and should not be regarded as limiting.

As mentioned above, an exemplary or representative distributed solid-state lighting system comprises a central power source coupleable to an AC input power source, and one or more terminal lighting apparatuses coupled to and spaced apart from the central power source. FIG. **1** is a block diagram illustrating an exemplary or representative lighting system **100**, an exemplary or representative central (host) power source **125**, and a first exemplary or representative terminal

LED lighting apparatus **150**. Referring to FIG. **1**, a lighting system **100** comprises a central (host) power source **125** and one or more terminal LED lighting apparatuses **150**. The one or more terminal LED lighting apparatuses **150** are coupled, in parallel, to a power transmission line **195** coupled to the central (host) power source **125**. Any number of terminal LED lighting apparatuses **150** may be utilized, up to the driving capacity of the central (host) power source **125**. The power transmission line **195** may be any type of power distribution line, currently known or developed in the future, with any corresponding power rating, such as a typical 2, 3, or 4 or more wire system found in a typical home, office, factory, etc., rated for 15-30 A, for example and without limitation.

For example and without limitation, in an exemplary or representative embodiment, a central (host) power source **125** may be embodied to have a legacy-compatible form factor and installed in a standard junction box to replace an existing or legacy light switch, such as a triac-based dimmer switch. Similarly, in a first alternative, terminal LED lighting apparatuses **150** may be embodied as LED bulbs and/or luminaires compatible with existing or legacy form factor and interface standards, such as typical

Edison-based sockets and interfaces, e.g., E12, E14, E26, E27, or GU-10 lighting standards, and following the input of operational parameters into the central (host) power source **125** as discussed below, may be inserted into existing lighting sockets to replace legacy incandescent or CFL bulbs, also for example and without limitation. A central (host) power source **125** and a terminal LED lighting apparatuses **150**, of course, are not required to be compatible with existing or legacy systems, and in other embodiments, may have any selected or desired form factor and electrical interface. Accordingly, in a second alternative, terminal LED lighting apparatuses **150** may be embodied as LED bulbs and/or luminaires which have a new and different form factor and/or interface (e.g., so that they are not inserted by mistake into a legacy socket which is not coupled to a central (host) power source **125**), and following the input of operational parameters into the central (host) power source **125** as discussed below, may be inserted into corresponding lighting sockets configured to the new and different interface standard, also for example and without limitation.

The system **100**, therefore, is not required to and generally does not utilize LED driver circuitry which is co-located with the LEDs, such as an AC/DC rectifier or a DC/DC converter. Rather, a distributed system **100** is implemented, with centrally located drive and control circuitry, along with some or no distributed control and regulation circuitry which may be co-located with the LEDs, depending upon the desired sophistication of the selected terminal LED lighting apparatus **150**.

An exemplary or representative central (host) power source **125** typically comprises an AC/DC rectifier **105**, a DC/DC converter **110**, a central (host) controller **120**, and a user interface **135**. The AC/DC rectifier **105** is coupled to an alternating current ("AC") line **130**, also referred to herein equivalently as an AC power line or an AC power source, such as a household AC line or other AC mains power source provided by an electrical utility, and converts the input AC voltage and current to DC. The AC/DC rectifier **105** may be any type of rectifier, currently known or developed in the future, such as a full-wave rectifier, a full-wave bridge, a half-wave rectifier, an electromechanical rectifier, or another type of rectifier, for example and without limitation. The direct current ("DC") voltage/current from the AC/DC rectifier **105** is then up converted to a higher DC voltage/current level or down converted to a lower DC voltage/current level using DC/DC converter **110**, which may be any type of DC/DC converter having any configuration, currently known or developed in the future, such as a buck converter, a boost converter, a buck-boost converter, a flyback converter, etc., and may be operated in any number of modes (discontinuous current mode, continuous current mode, and critical conduction mode), any and all of which are considered equivalent and within the scope of the present invention, for example and without limitation.

The DC/DC converter **110** is controlled by the central (host) controller **120**, which receives one or more feedback signals from the DC/DC converter **110** and which provides one or more current and/or voltage set or other control signals to the DC/DC converter **110**, based upon user input, such as a selected dimming level or color temperature, and based upon the input of various operational parameters for the system **100**. Based upon such user preferences and input operational parameters, as discussed in greater detail below, the central (host) controller **120** calculates or otherwise determines the voltage and/or current settings for one or more control signals provided to the DC/DC converter **110**, to control the output DC voltage, current and/or power levels provided as input voltage, current and/or power levels to the terminal LED lighting apparatuses **150**. For example, the DC/DC converter **110** typically includes a MOSFET (not separately illustrated) operable in a linear mode (and also typically in a saturation mode) and under the control of one or more control signals provided by the central (host) controller **120**, to raise or lower the output DC voltage, current and/or power levels. The various operational parameters for the system **100**, such as maximum and minimum voltage, current and/or power levels, discussed in greater detail below, are provided to the central (host) controller **120** via the user interface **135**, and may be stored in a memory (typically non-volatile) that may be provided within the central (host) controller **120** or stored within an optional memory **115**. Also as described in greater detail below, these various operational parameters may be varied throughout the use and lifetime of the system **100** such as, for example, when any of the one or more terminal LED lighting apparatuses **150** are removed or replaced. The central (host) controller **120** (and any optional memory **115**) may be implemented as currently known or developed in the future, as described in greater detail below, such as using a processor, a controller, a state machine, combinational logic, etc., for example and without limitation.

Also illustrated in FIG. **1** are various optional input and output ("I/O") devices and articles of manufacture which may be utilized with or incorporated within a user interface **135** and/or **165** for system display and input of user preferences and operational parameters for the system **100**, illustrated as wireless remote control **175**, machine-readable encoded fields **170** (e.g., a non-transitory, scannable (or otherwise tangible and machine-readable) encoded article of manufacture such as a UPC-type barcode or a QR ("Quick Response") code), a display **190** (such as a touch screen display, an LED display, an LCD display, etc.), a switch control **185** (such as an on/off switch, a dimming input (e.g., dimming knob, slideable dimming control, or control button(s)), and/or a keypad **180**, any of which may be implemented as currently known or developed in the future. While the user interfaces **135**, **165** are illustrated as having wireless communication capability (e.g., Bluetooth, IR, IEEE 802.11, etc.), in various exemplary embodiments, any of the various controllers **120**, **160** instead may be implemented to have such wireless capability for user communication.

An exemplary or representative terminal LED lighting apparatus **150** comprises one or more light emitting diodes ("LEDs") **140**, and optionally and in any of various combinations, may further comprise a current source (or regulator) **145**, a terminal (or remote) controller **160**, one or more sensors **155**, a user interface **165**, and potentially an optional memory circuit (not separately illustrated, and which also may be included within a terminal (or remote) controller **160**). One or more exemplary or representative terminal LED lighting apparatuses **150** are typically distributed in different locations within one or more rooms of an office, house, etc., and are coupled in parallel to power transmission line **195**, each via a corresponding current source (or regulator) **145**, to receive power from the DC/DC converter **110** of the central (host) power source **125**. Those having skill in the electronic arts will recognize that instead of utilizing a current source (or regulator) **145**, a power regulator (not separately illustrated) may be utilized equivalently, controlling the power (both current and voltage) provided to the LEDs **140**. Accordingly, use of such a power regulator is considered equivalent and within the scope of the disclosure.

The current source (or regulator) **145** may be implemented to be quite simple or complex, as currently known or developed in the future, with many exemplary or representative embodiments illustrated in greater detail below, and provides power (voltage and current) to the LEDs **140**, which may be any type or kind of LEDs, currently known or developed in the future, with any corresponding lumen output, color temperature, power, current and voltage ratings, and which may have any of various configurations, such as parallel, serial, and/or combinations of both. In other exemplary embodiments, the current source (or regulator) **145** may be optional and omitted, or otherwise may have so few components that regulation is minimal, such as merely providing current and temperature overload protection. The terminal (or remote) controller **160** also may include internal memory capabilities and may be implemented as currently known or developed in the future, as described in greater detail below, such as using a processor, a controller, a state machine, combinational logic, etc., also for example and without limitation. Optional sensors **155** and user interface **165** may be implemented to be simple or complex, as currently known or developed in the future, with many exemplary or representative embodiments illustrated in greater detail below. For example and without limitation, a sensor **155** may be implemented as a current sense resistor or a voltage divider. Also for example, a user interface **165** may be implemented simply to receive wireless signals (e.g., for dimming or color temperature control over the individual terminal LED lighting apparatuses **150**) from a wireless remote control **175**.

As illustrated in FIG. **1**, the terminal LED lighting apparatus **150** is particularly suitable for dimming applications. Other embodiments of terminal LED lighting apparatuses **150** are also illustrated with fewer components (e.g., only current and temperature overload protection) and, of course, allows less control over output brightness levels. Referring to FIG. **1**, the exemplary or representative terminal LED lighting apparatus **150** utilizes the terminal (or remote) controller **160** to receive feedback signals from one or more sensors **155** (such as any of LED current levels, output power, LED DC voltage levels, etc.), receive user input via remote user interface **165**, and provide control signals (such as LED set current levels for a desired dimming level) to the current source (or regulator) **145**. As mentioned above, the terminal LED lighting apparatus **150** may be operated in any of various modes, such as continuous current mode, discontinuous current mode, or other modes, any and all of which are within the scope of the disclosure.

The central (host) controller **120** (and, therefore, also the central (host) power source **125** and system **100**) has three operational modes: a set (or set up) operational mode, an automatic operational mode, and an exchange operational mode). As discussed in greater detail below with reference to FIG. **15**, in exemplary embodiments, the terminal LED lighting apparatus **150** housing and/or its labeling or packaging includes an article of manufacture comprising one or more machine-readable encoded fields **170**, such as a scannable (or otherwise machine-readable) barcode or QR code, which includes a plurality of data fields encoding operational parameter information, such as minimum and maximum voltage and current levels for the selected type of terminal LED lighting apparatus **150** (or, as another option, for its incorporated string of LEDs **140**). Other optional parameters may also be included within the machine-readable encoded fields **170**, such as maximum or minimum power levels, maximum operating temperature, etc. During set up (or set) or exchange operational modes, such machine-readable encoded fields **170** are scanned or otherwise read through the user interface **135**, a display **190**, or wireless remote control **175**, or another device which may function as such a remote control **175**, such as a smartphone with a corresponding scanning application, as known or developed in the future. In addition to UPC barcodes and QR encoding, any other type of machine-readable data encoding (and corresponding reading and uploading method) is considered equivalent and within the scope of the disclosure, including those that merely provide an index, link, number or identification into a look up table stored in a memory and having the corresponding operational parameters. The operational parameters for each terminal LED lighting apparatus **150** are thereby uploaded into the user interface **135** and stored in a memory **115** or internal memory of a central (host) controller **120**, and the corresponding terminal LED lighting apparatus **150** may then be installed (e.g., inserted into a socket) of the system **100**. Similarly, during an exchange mode, operational parameters may be deleted from memory for a terminal LED lighting apparatus **150** that is being removed from the system **100**, also by scanning of its machine-readable encoded fields **170**, and the operational parameters of the replacement terminal LED lighting apparatus **150** are then scanned and thereby uploaded into the central (host) power source **125**. This creates significant flexibility for the system **100** over its lifetime, which is not constrained by static operational parameters that are fixed by a manufacturer during device assembly, and instead may be modified and adjusted for user preferences and use of different types of terminal LED lighting apparatuses **150**, including those from different manufacturers.

It should also be understood, however, that in the event machine-readable encoded fields **170** are not available for any reason, the corresponding data may be entered (and deleted) manually, such as through other devices, such as display **190** (e.g., a touchscreen) or keypad **180**.

In addition, while system **100** is illustrated with the central (host) power source **125** functioning as a 2-way switch, those of skill in the art will recognize that the central (host) power source **125** may be easily extended to 3-way embodiments, 4-way embodiments, etc.

FIG. **2** is a flow diagram illustrating an exemplary or representative preoperational method for set up and exchange modes of an exemplary or representative lighting system **100** and an exemplary or representative central (host) power source **125**. Beginning with start step **200**, via user interface **135** or remote control **175**, a user may have the central (host) power source **125** enter the exchange mode, step **205**, such as to remove a failed LED bulb and replace it with a new one. The user may remove a terminal LED lighting apparatus **150**, such as a failed LED bulb, from its current location, step **210**, and delete the corresponding operational parameters from memory, such as by scanning the machine-readable encoded fields **170**, step **215**. When an additional terminal LED lighting apparatus **150** is to be removed, step **220**, the method returns to steps **210** and **215**. When all terminal LED lighting apparatuses **150** have been removed, step **220**, or when the user has the central (host) power source **125** enter the set up mode in step **225**, new operational parameters of a new or replacement terminal LED lighting apparatus **150** are input via user interface **135** or remote control **175** and stored in memory, such as optional memory **115** or a memory within central (host) controller **120**, step **230**. The user then installs a new or replacement terminal LED lighting apparatus **150**, such as by screwing it into a standard socket, step **235**. When an additional terminal LED lighting apparatus **150** is to be added, step **240**, the method returns to step **230**. When all terminal LED lighting apparatuses **150** have been added, step **240**, the central (host) controller **120** may then calculate or otherwise determine the nominal output voltage, current and/or power levels to be provided by the DC/DC converter **110** and other parameters, step **245**, as discussed in greater detail below, and the method may end, return step **250**.

Typically, a dimming level is set by user interface **135** (manually) or by a remote control **175**. In set mode, the central (host) controller **120** gets information from the machine-readable encoded fields **170** via the user interface **135** to set the maximum (and/or minimum) operational parameters of the central (host) power source **125** and saves this in the memory as a network configuration, including the number of terminal LED lighting apparatus **150***es* and their operational parameters, such as maximum voltages, current, power, etc. In exchange mode, the central (host) controller **120** gets the corresponding information on the failed terminal LED lighting apparatus **150** and the new, replacement terminal LED lighting apparatus **150**, and recalculates or reconfigures the system **100** (or network) settings. Depending upon the degree of sophistication of the system **100**, the information input during set and exchange modes may also include the (network) location of the particular terminal LED lighting apparatus **150** within the system **100**. In automatic mode, the central (host) controller **120** performs various calculations, discussed below, provides corresponding control signals to the DC/DC converter **110**, and sets the dimming level for the terminal LED lighting apparatuses **150** based on the signals from the remote control **175** or user interface **135** (e.g., which may be manually input via display **190**, switch control **185**, or keypad **180**).

In an exemplary embodiment, the central (host) controller **120** calculates or otherwise determines the dimming level "ρ" for the plurality of terminal LED lighting apparatuses **150**, in which (Equation 1):

$$\rho = \frac{I_{out}}{I_{outn}},$$

where Iout is the LED **140** current in a terminal LED lighting apparatus **150** for a user determined or selected dimming level and Ioutn is the nominal LED **140** current in a terminal LED lighting apparatus **150** with no dimming (e.g., full brightness). In turn, Iout and Ioutn are related as follows (Equation 2):

$$I_{out} = I_{outn}\left(1 - \frac{V_{inmax} - V_{in}}{V_{inmax} - V_{inmin}}\right),$$

where Vin is the input voltage to the terminal LED lighting apparatus **150**, Vinmax is the maximum input voltage to the terminal LED lighting apparatus **150**, Vinmin is the minimum input voltage to the terminal LED lighting apparatus **150**, resulting in the dimming level "ρ" (Equation 3):

$$\rho = \left(1 - \frac{V_{inmax} - V_{in}}{V_{inmax} - V_{inmin}}\right).$$

In turn, the relationship between the input voltage to the terminal LED lighting apparatus **150** and the selected dimming level is (Equation 4):

$$Vin = \rho(V_{inmax} - V_{inmin}) + V_{inmin},$$

or Equation 5:

$$Vin = \rho\Delta Vinmax + Vinmin$$

where (Equation 6):

$$\Delta Vinmax = Vinmax - Vinmin$$

A dimming transfer function "μ" may then be calculated or otherwise determined as (Equation 7):

$$\mu = \frac{I_{out}}{V_{in}} = \frac{\Delta V_{in} I_{outn}}{\Delta V_{inmax} V_{in}},$$

where ΔVin=Vin−Vinmin, namely, the change in input voltage provided to the terminal LED lighting apparatus **150** from the minimum voltage input to the terminal LED lighting apparatus **150**, where Vin the sensed input voltage of the terminal LED lighting apparatus **150**. (Equivalently, ΔVin could be defined as a change from the maximum input voltage, where ΔVin=Vinmax−Vin, namely, the change in input voltage provided to the terminal LED lighting apparatus **150** from the nominal or maximum voltage input to the terminal LED lighting apparatus **150** without dimming, also where Vin the sensed input voltage of the terminal LED lighting apparatus **150**.) For example, using the calculated transfer function μ, each terminal (or remote) controller **160** may calculate or otherwise determine the current to be provided to LEDs **140** as (Equation 8):

$$Iout = \mu Vin.$$

As discussed in greater detail below, this relationship between input voltage and current to be provided to the LEDs **140** is quite powerful and highly novel, as dimming control can be provided to each terminal LED lighting apparatus **150** by a change in the output voltage provided by the central (host) power source **125**. Sensing the input voltage Vin, the terminal (or remote) controller **160** then determines the appropriate, corresponding current level Iout to be provided to the LEDs **140**, thereby raising or lowering (dimming) the output brightness level accordingly. This is very different than prior art dimming through a triac-based device, which provides dimming by clipping or eliminating a portion of the AC voltage/current provided to the lamp.

It should also be noted that while the various exemplary equations and transfer function illustrate a linear relationship between the input voltage Vin and the current level Iout to be provided to the LEDs **140**, nonlinear relationships are also within the scope of the disclosure and considered equivalent (and are illustrated and discussed with reference to FIG. 4).

Assuming that voltage drop in the transmission power line **195** is negligible, the output voltage of the central (host) power source **125** can be considered to be effectively equal to the input voltage to the terminal LED lighting apparatuses **150**, such that (Equations 8, 9, 10 and 11):

$$Vout=Vin;$$

$$Voutmin=Vinmin;$$

$$Voutmax=Vinmax; \text{ and}$$

$$\Delta Voutmax=\Delta Vinmax.$$

It should be noted, for each of these parameters, when a DC voltage and current are not being utilized, such as in the high frequency system discussed below, the voltage and current amplitudes may be utilized equivalently for these calculations. As a result, the central controller **120** may determine the second DC voltage level Vout as (Equation 12): Vout=ρΔVoutmax+Voutmin, in which "ρ" is a user selectable brightness level and corresponds to

$$\rho = \frac{I_{out}}{I_{outn}},$$

ΔVoutmax=Voutmax−Voutmin, Iout is the selected current level of the plurality of light emitting diodes **140** for one or more terminal lighting apparatuses **150**, Ioutn is the nominal current level of the plurality of light emitting diodes **140** for one or more terminal lighting apparatuses **150**, Voutmax=Vinmax in which Vinmax is the maximum input voltage to the one or more terminal lighting apparatuses **150**, and Voutmin=Vinmin in which Vinmin is the minimum input voltage to the one or more terminal lighting apparatuses **150**. Similarly, the terminal controller **160** may determine the LED current Iout as linearly proportional to the input voltage Vin (Equation 13): Iout=μVin, where μ is a linear transfer function,

$$\mu = \frac{(V_{in} - V_{inmin})I_{outn}}{\Delta V_{inmax} V_{in}},$$

in which ΔVinmax=Vinmax−Vinmin, Iout is the selected current level of the plurality of light emitting diodes **140** for one or more terminal lighting apparatuses **150**, Ioutn is the nominal current level of the plurality of light emitting diodes **140** for one or more terminal lighting apparatuses **150**, Vinmax is the maximum input voltage to the one or more terminal lighting apparatuses **150**, Vinmin is the minimum input voltage to the one or more terminal lighting apparatuses **150**, and Vin the sensed input voltage of the one or more terminal lighting apparatuses **150**.

As part of the set up or exchange process (step **245**), or upon powering on (powering up) of the system **100**, the parameters Vout, Voutmin, Voutmax, and ΔVoutmax may be calculated by the central (host) controller **120** using the various input operational parameters and the number of terminal LED lighting apparatuses **150** in the system **100**, or may be input via user interface **135** or remote control **175**. Similarly, the parameters Ioutn, Vinmin, Vinmax and ΔVinmax (and other parameters) for one or more terminal LED lighting apparatuses **150** may be provided directly to the terminal LED lighting apparatus(es) **150** by the manufacturer as part of or otherwise during device manufacture (e.g., input and stored in a terminal (or remote) controller **160** and its associated memory (not separately illustrated)), or may be calculated by the terminal (or remote) controller **160** using its input operational parameters, or may be input via remote user interface **155** or remote control **175**. As yet another alternative, during either set up (or exchange mode) or powering on, the central (host) power source **125** may transmit these values to the terminal LED lighting apparatuses **150**, such as through various handshaking mechanisms and/or power line signaling.

FIG. **3** is a flow diagram illustrating an exemplary or representative method of operating an exemplary or representative lighting system **100**, an exemplary or representative central (host) power source **125**, and an exemplary or representative terminal LED lighting apparatus **150**. The automatic mode method begins, start step **300**, when the system **100** is powered on by the user, and the user selects a brightness level, such as by pressing a button, flipping a switch, or moving a slideable indicator, for example and without limitation. (As part of step **300**, if not performed as step **245** mentioned above, the various operational parameters mentioned above may be determined and stored in the memories of the central (host) power source **125** and the terminal LED lighting apparatus **150**.) The central (host) controller **120** determines what brightness level has been selected, step **305**, and calculates or determines a dimming level ρ, step **310**, that corresponds to the selected brightness level. Based on the dimming level ρ, in step **315**, the central (host) controller **120** determines the output voltage and/or current levels, with Vout=ρΔVoutmax+Voutmin, and provides corresponding control signals, to the DC/DC converter **110**. For example, the calculated value of Vout may be provided as a reference voltage level in a feedback loop within the central (host) controller **120** or the DC/DC converter **110**. The AC/DC rectifier **105** rectifies the input AC voltage and the DC/DC converter **110**, using the control signals from the central (host) controller **120**, provides power, as the corresponding DC output voltage and current levels, to the terminal LED lighting apparatuses **150** over power transmission line(s) **195**, step **320**. The central (host) controller **120** monitors the DC output voltage and current levels, and provides any feedback signals to the DC/DC converter **110** to maintain the desired DC output voltage and current levels, step **325**. When the system **100** has not been powered off, step **330**, the method continues, and determines whether there has been any change in the selected dimming level, step **335**. When there is a change to the selected dimming level, step **335**, the method iterates, returning to step **305** and repeating steps **305-330**, and continues to provide the selected DC output voltage and current levels at the new dimming level. When the system **100** has been powered off, step **330**, the method may end, return step **370**.

As long as the system **100** has not been powered off, the method continues and the terminal LED lighting apparatuses **150** continue to receive input power from the DC/DC converter **110** at the selected DC output voltage and current levels. Continuing to refer to FIG. **3**, a terminal (or remote) controller **160** monitors (senses and/or measures) the input voltage level (and/or current level) to the terminal LED lighting apparatus **150**, such as through a voltage sensor, step **340**, and calculates or otherwise determines the dimming transfer function μ and calculates of otherwise determines Iout, step **345**. For example, the transfer function may be calculated as

$$\mu = \frac{(V_{in} - V_{inmin})I_{outn}}{\Delta V_{inmax} V_{in}},$$

and the current Iout may be calculated as Iout=μVin, by digital or analog devices, as mentioned above. The terminal (or remote) controller **160** sets the LED **140** current level to the calculated value of Iout, such as by providing control signals to the current source (or regulator) **145**, step **350**, and the current source (or regulator) **145** provides power to the LEDs **140** at this set current level Iout, step **355**. Using sensor (s) **155**, the terminal (or remote) controller **160** monitors the LED **140** current (and/or voltage) levels, provides feedback signals to the current source (or regulator) **145** to adjust or maintain the LED **140** current (and/or voltage) levels at the selected Iout level (or a lower level, if needed, based on input parameters, such as maximum current levels, for example), step **360**. When there has been no change in the input voltage level (and/or current level) to the terminal LED lighting apparatus **150**, step **365**, the method continues, returning to step **355** to continue providing power to the LEDs **140**. When there is a change in the input voltage level (and/or current level) to the terminal LED lighting apparatus **150**, step **365**, the method returns to step **345** and iterates.

It should also be noted that instead of calculating a transfer function in step **345**, a terminal (or remote) controller **160** may also be configured to utilize the sensed input voltage Vin (or corresponding current level) as an index into a look up table, stored in memory, which then provides a corresponding level of Iout which may be utilized to set the LED **140** current level. In addition, as illustrated in FIG. **4**, various nonlinear transfer functions may also be utilized.

It should be noted and those having skill in the art will recognize that the steps illustrated in FIG. **3** may occur in a wide variety of orders, and may operate as simultaneous, iterative loops until the system **100** is powered off, a first loop occurring at the central (host) power source **125**, and a second loop occurring at each of the terminal LED lighting apparatus **150**. In addition, various steps are continuous, such as monitoring step **340**, which operates as long as the system **100** is powered on. For a first loop occurring at the central (host) power source **125**, for example, unless the system **100** is powered off, and unless there is a change in the dimming level, step **320** continues, in which the AC/DC rectifier **105** rectifies the input AC voltage and the DC/DC converter **110**, using the control signals from the central (host) controller **120**, continues to provide the same level of DC output voltage and current levels to the terminal LED lighting apparatuses **150** over power transmission line(s) **195**. Also unless powered off, when there is a change in the dimming level, the method will iterate to generate new DC output voltage and current levels to the terminal LED lighting apparatuses **150**, and will continue to provide this new level until the dimming level changes again or the system is powered down. Similarly, for a second loop occurring at the terminal LED lighting apparatuses **150** (generally simultaneously with the first loop once in steady state), unless there is a change in the input voltage level (and/or current level), current (and/or voltage) will continue to be provided to the LEDs **140** at the set level of Iout, with corresponding feedback control (steps **355** and **360**). When there is a change in the input voltage (and/or current) level, the method will also iterate to generate a new current level Iout and provide power to the LEDs **140** at this new current level.

FIG. **4** is a graph illustrating exemplary or representative voltage and current waveforms for intelligent dimming using an exemplary or representative lighting system **100**, an exemplary or representative central (host) power source **125**, and an exemplary or representative terminal LED lighting apparatus **150**, and provides a useful summary of the dimming methodology described above. As discussed above, when powered on, the central (host) power source **125** will provide an output voltage corresponding to a desired dimming level, which is the input voltage Vin to the terminal LED lighting apparatus **150**, and which varies between a minimum input voltage Vinmin and a maximum input voltage Vinmax, illustrated as line **251**. Based upon the input voltage Vin, the terminal (or remote) controller **160** determines the level of LED **140** current Iout that provides the selected dimming level, which may be a linear relationship between Vin and Iout illustrated as line **252**, or any of various nonlinear relationships, illustrated as lines **253** and **254** for example. For example, an input voltage Vin sensed at level "A", would map through the corresponding transfer function to an LED **140** current Iout having a level "B" for the linear transfer function illustrated as line **252** and also for the nonlinear (sigmoidal) transfer function illustrated as line **254**, but would map through the corresponding transfer function to an LED **140** current Iout having a level "C" for the nonlinear transfer function illustrated as line **253**. Those having skill in the art will recognize that there are advantages to each of these transfer functions, such as the degree of lighting control which may be provided to the user in different regions of dimming, e.g., finer control in certain percentage intervals or equal control throughout the entire 0% to 100% dimming. Using the variation in input voltage Vin, the terminal (or remote) controller **160** is able to correspondingly adjust the LED **140** current level from no (0%) dimming to 100% dimming (when the voltage level is insufficient to turn on the LEDs **140** and no current flows through the LEDs **140**). In addition, such dimming of the LEDs **140** is provided without any issues of stability, flicker, or the other problems associated with prior art triac-based dimming.

Referring again to FIG. **3**, those having skill in the art will also recognize that many of the illustrated steps may be omitted or varies, and will depend in large part upon the type of terminal LED lighting apparatus **150** utilized within the system **100**. A wide variety of exemplary or representative types of terminal LED lighting apparatuses **150** are illustrated and discussed below with reference to FIGS. **5-14**. For example, several illustrated examples of terminal LED lighting apparatuses **150** do not include any terminal (or remote) controller **160**, any sensors **155**, or any remote user interface **165**, and for those embodiments, only steps **300**, **315**, **320**, **325**, **330** and **370** may be executed, with all other steps omitted. For these implementations, most of the lighting control is performed by the central (host) power source **125**, with limited control by the terminal LED lighting apparatus **150** (e.g., current and/or temperature overload control, passive current control, etc.). For some of these embodiments, dimming may occur by varying the output voltage Vout of the central (host) power source **125**, thereby increasing or decreasing LED **140** current passively within the terminal LED lighting apparatus **150**.

It should also be noted that depending upon the type of terminal LED lighting apparatus **150** utilized in the system **100**, different operational parameters may be utilized to determine the output voltage Vout of the central (host) power source **125**, such as the minimum or the maximum current ratings of the selected terminal LED lighting apparatus **150**. In addition, those having skill in the art will also recognize that while several different types of terminal LED lighting apparatuses **150** may be utilized concurrently within the system **100**, in other circumstances, only one type of terminal LED lighting apparatus **150** should be selected for implementation of a selected system **100**.

It should also be noted that depending upon the implementation of a system **100**, different types of wiring may be utilized, in addition to power transmission lines **195**, such as communication wiring, which may allow for additional data communication between and among the central (host) power source **125** and the terminal LED lighting apparatuses **150**. In addition, additional control and data transmission may be provided using various power line signaling methods known or developed in the future. Also, depending upon the implementation, wireless communication may also occur between and among the central (host) power source **125** and the terminal LED lighting apparatuses **150** using the wireless capabilities which may be implemented in the user interfaces **135**, **165**. This additional potential for control may be utilized, for example and without limitation, for color mixing and temperature control (e.g., FIG. **14**) and for differential dimming among the terminal LED lighting apparatuses **150**. For example, such differential dimming may be performed using network addresses for the terminal LED lighting apparatuses **150** within the system **100** and power line signal or wireless communication.

FIG. **5** is a block and circuit diagram illustrating a second exemplary or representative terminal LED lighting apparatus **150**A for use in a comparatively low voltage DC system **100**A, in which the output voltage Vout of the central (host) power source **125** is a comparatively lower DC voltage, typically less than about 60V DC (to provide self-voltage capability), indicated by designating the power transmission line as low voltage DC lines **195**A. In addition to terminal LED lighting apparatuses **150**A being able to be used in such a system **100**A, other types of terminal LED lighting apparatuses **150** (**150**F, **150**G, **150**H, and **150**J illustrated in FIGS. **11-14**) may also be utilized in a comparatively low DC voltage system **100**A. As illustrated in FIG. **5**, central (host) power source **125** is coupled to an AC input **130**, and a plurality of terminal LED lighting apparatuses **150**A are connected in parallel to the transmission lines **195**A. The selection of self-powering voltage allows the terminal LED lighting apparatus **150**A to employ a low voltage topology. As illustrated, the current source (or regulator) **145**A utilizes a buck topology comprised of inductor **408**, diode **406**, and MOSFET **404**, using a current sense resistor **402** as a sensor **155**A, and using a terminal (or remote) controller **160**. The series connected string of LEDs **140** is driven by a current regulated source, and the LEDs **140** do not require binning during manufacturing. While a buck converter is illustrated, any other type of converter may be utilized equivalently, including buck-boost, sepic, flyback, and many others currently known or developed in the future.

FIG. **6** is a block and circuit diagram illustrating a third exemplary or representative terminal LED lighting apparatus for use in a comparatively high voltage DC system **100**B, in which the output voltage Vout of the central (host) power source **125** is a comparatively higher DC voltage, in the range of about 300V, for example and without limitation, indicated by designating the power transmission lines as low voltage DC lines **195**B. As illustrated in FIG. **6**, central (host) power source **125** is coupled to an AC input **130**, and a plurality of terminal LED lighting apparatuses **150**B are connected in parallel to the transmission lines **195**B. As illustrated, the current source (or regulator) **145**B utilizes a high voltage flyback topology comprising transformer **410**, snubber circuit **412**, rectifier (diode) **414**, filter capacitor **416**, and MOSFET **418**, using a current sense resistor **402** as a sensor **155**A, and using a terminal (or remote) controller **160**.

FIG. **7** is a block diagram illustrating an exemplary or representative system **100**C having both comparatively high and low DC levels, respectively illustrated using transmission lines **195**B and **195**A, and with an additional DC/DC converter **110**A to convert the higher voltage on lines **195**B to a lower DC voltage on lines **195**A.

FIG. **8** is a block and circuit diagram illustrating a fourth exemplary or representative terminal LED lighting apparatus **150**C for use in a comparatively high frequency system **100**D, which can be either a comparatively high or low voltage AC, and may have a wide range of suitable frequencies (e.g., about 500 Hz to 90 kHz), such as 60 kHz, for example and without limitation, indicated by designating the power transmission lines as high frequency lines **195**C. As illustrated in FIG. **8**, central (host) power source **125**A is coupled to an AC input **130**, and a plurality of terminal LED lighting apparatuses **150**C are connected in parallel to the transmission lines **195**C. Not separately illustrated, the central (host) power source **125**A for this embodiment will generally also comprise a high frequency inverter to create the high frequency AC voltage on lines **195**C. As illustrated, the current source (or regulator) **145**C comprises a high frequency transformer **420**, a rectifier **422** (e.g., a bridge rectifier), an optional filter capacitor **424**, and may also include an additional current regulator (not separately illustrated) connected between the rectifier **422** and the capacitor **424**. The optional filter capacitor **424** may be utilized to effectively remove any appreciable voltage ripple and provide flicker-free drive of the LEDs **140**. An advantage of this topology is the comparatively small size of the current source (or regulator) **145**C due to the small size of the high frequency transformer **420**. Such a high frequency current source (or regulator) **145**C may be implemented using a wide variety of topologies, currently known or developed in the future, such as those illustrated in FIGS. **9** and **10** discussed below.

FIG. **9** is a block and circuit diagram illustrating a fifth exemplary or representative terminal LED lighting apparatus **150**D for use in a comparatively high frequency system **100**E, which also can be either a comparatively high or low voltage AC, and may have a wide range of suitable frequencies (e.g., about 500 Hz to 90 kHz), such as 60 kHz, for example and without limitation, as discussed above. As illustrated in FIG. **9**, central (host) power source **125**A is coupled to an AC input **130**, and a plurality of terminal LED lighting apparatuses **150**D are connected in parallel to the transmission lines **195**C. Also not separately illustrated, the central (host) power source **125**A for this embodiment will generally also comprise a high frequency inverter to create the high frequency AC voltage on lines **195**C. As illustrated, the current source (or regulator) **145**C is also utilized, as discussed above. In this embodiment, which may be very effective at high frequency, a plurality of switches **426** are utilized to selectively bypass selected LEDs **140** of the illustrated plurality of series-connected LEDs **140**. Initially, when the AC voltage is low (e.g., near a zero crossing), all of the switches are on and only a few or minimal number of LEDs **140** are connected in series to receive power (via rectifier **422** and transformer **420**). As the instantaneous AC voltage increases, more LEDs **140** are switched into the series-connected path of LEDs **140**, such as by sequentially turning off switches **426**, and as the instantaneous AC voltage decreases, more LEDs **140** are switched out of the series-connected path of LEDs **140**, such as by sequentially turning on switches **426**. The optional filter capacitor

424 also may be utilized to effectively remove any appreciable voltage ripple and provide flicker-free drive of the LEDs 140.

FIG. 10 is a block and circuit diagram illustrating a sixth exemplary or representative terminal LED lighting apparatus 150E for use in a comparatively high frequency system 100F, which also can be either a comparatively high or low voltage AC, and may have a wide range of suitable frequencies (e.g., about 500 Hz to 90 kHz), such as 60 kHz, for example and without limitation, as discussed above. As illustrated in FIG. 10, central (host) power source 125A is coupled to an AC input 130, and a plurality of terminal LED lighting apparatuses 150E are connected in parallel to the transmission lines 195C. Not separately illustrated, the central (host) power source 125A for this embodiment also will generally also comprise a high frequency inverter to create the high frequency AC voltage on lines 195C. As illustrated, the current source (or regulator) 145D comprises a high frequency transformer 420, a rectifier 422 (e.g., a bridge rectifier), and a capacitor 428, which may be coupled on either the primary or the secondary side of the transformer 420. The capacitor 428 adds and additional impedance in series with the LEDs 140 and may be utilized to effectively improve their VA (Volt and Ampere) characteristics, providing a more stable current with voltage variation. The total impedance will be (Equation 12):

$$Z = \sqrt{X_c^2 + \frac{1}{K_t^4} R_{LED}^2},$$

where Xc is the impedance of the capacitor 428, Kt is the transformer ratio, and R_{LED} is the equivalent LED 140 impedance.

FIG. 11 is a block and circuit diagram illustrating a seventh exemplary or representative terminal LED lighting apparatus 150F for a comparatively low voltage DC system 100A, such as illustrated in FIG. 5 and discussed above for other terminal LED lighting apparatuses 150A. An exemplary or representative terminal LED lighting apparatus 150F is coupleable to transmission power lines 195A, and comprises a plurality of LEDs 140 coupled in series to a current source (or regulator) 145E comprising very few components, namely, a fuse 432 and a thermal current regulator 434. For this comparatively simple terminal LED lighting apparatus 150F embodiment, the fuse 432 operates as known in the art to open circuit at or above a predetermined LED 140 current, while the thermal current regulator 434 will reduce the LED 140 current if the temperature of the terminal LED lighting apparatus 150F exceeds a predetermined threshold and thereby keep the LED 140 current within predetermined limits, and allowing use of the terminal LED lighting apparatus 150F with a central (host) power source 125 with an output voltage rout which may produce a wide range of LED 140 currents. As discussed above, as an option, such an embodiment may also include in its housing, labeling and/or packaging, machine-readable encoded fields 170 which may be scanned into the central (host) power source 125 during set up or during exchange modes, which will typically include encoded information for minimum and maximum voltage and minimum and maximum current for the terminal LED lighting apparatuses 150F, and possibly a network address for the apparatus 150F. As mentioned above, these maximum and minimum voltage and current parameters may also be provided on the basis of minimum and maximum LED 140 voltage levels, minimum and maximum LED 140 current, for the incorporated string of LEDs 140. These operational parameters may also be manually entered, as discussed above. For example, for this embodiment, minimum input voltage and minimum input current levels for the terminal LED lighting apparatus 150F are typically entered and stored in the central (host) power source 125.

A plurality of terminal LED lighting apparatuses 150F may be utilized in a system 100A up to the power capacity of the central (host) power source 125, with operational parameters input into the system 100A during set up and/or exchange modes as previously discussed. During operation (automatic mode), the central (host) power source 125 is turned on and provides a minimum output voltage Vout, and then typically progressively ramps up the output voltage Vout, typically below or up to a maximum Vout that is based on the minimum and maximum voltage and current parameters for the plurality of terminal LED lighting apparatuses 150F, so that at least minimum voltage and current are provided to the terminal LED lighting apparatuses 150F and the maximum voltage and current of the terminal LED lighting apparatuses 150F generally are not exceeded, as discussed above. For example, in an exemplary embodiment, during operation (automatic mode), Vout=Vinmin for the terminal LED lighting apparatuses 150F. Also or example, a Vout may be determined by the central (host) controller 120 to be based upon an output voltage that would be required to provide an output current which is greater than, by a selected percentage, the sum of the minimum LED 140 currents for all of the terminal LED lighting apparatuses 150F included within the system 100A, such as Vout=τ1.1Σ minimum I_{LED} (where τ is a transfer function or other conversion factor), or setting Voutmax=the minimum V_{LED}, or setting the output current of the central (host) power source 125=1.1Σ minimum I_{LED}, or based upon a range in between minimum and maximum voltage and current levels of the terminal LED lighting apparatuses 150F, such as maximum V_{LED}≥Vout≥minimum V_{LED}, or 1.1Σ minimum I_{LED}≤output current of the central (host) power source 125≤0.8Σ maximum I_{LED}, etc., for example and without limitation. For this embodiment, the output current and voltage of the central (host) power source 125 also is typically monitored, with feedback provided as discussed above, so that these current and voltage levels are within an acceptable margin and do not exceed the current and voltage limits discussed above for the plurality of terminal LED lighting apparatuses 150F.

FIG. 12 is a block and circuit diagram illustrating an eighth exemplary or representative terminal LED lighting apparatus 150G for a comparatively low voltage DC system 100A, such as illustrated in FIG. 5 and discussed above for other terminal LED lighting apparatuses 150A and 150F. An exemplary or representative terminal LED lighting apparatus 150G is coupleable to transmission power lines 195A, and comprises a plurality of LEDs 140 coupled to a current source (or regulator) 145F. For this representative embodiment, the current source (or regulator) 145F comprises a fuse 432, a current source 436 which is controlled by a voltage provided by a voltage divider comprising a plurality of resistors 433, 438, and 435, and zener diode 437. For this moderately complicated terminal LED lighting apparatus 150G embodiment, the fuse 432 also operates as known in the art to open circuit at or above a predetermined LED 140 current, while the control voltage provided to the current source 436 by the voltage divider components is typically stably fixed by the resistors 435, 438 and zener diode 437, with the current source 436 providing a comparatively constant LED 140 current limit. Also as discussed above, as an option, such an embodiment may also include in its housing, labeling and/or packaging, machine-readable encoded fields 170 which may be scanned into the central (host) power source **125** during set up or during exchange modes, which will typically include encoded information for minimum and maximum voltage and minimum and maximum current for the terminal LED lighting apparatuses **150**G, and possibly a network address for the apparatus **150**G. As mentioned above, these maximum and minimum voltage and current parameters may also be provided on the basis of minimum and maximum LED **140** voltage levels, and minimum and maximum LED **140** current levels, for the incorporated string of LEDs **140**. These operational parameters may also be manually entered, as discussed above. For example, for this embodiment, minimum input voltage and minimum input current levels for the terminal LED lighting apparatus **150**G are typically entered and stored in the central (host) power source **125**.

A plurality of terminal LED lighting apparatuses **150**G may be utilized in a system **100**A up to the power capacity of the central (host) power source **125**, with operational parameters input into the system **100**A during set up and/or exchange modes as previously discussed. During operation (automatic mode), the central (host) power source **125** is turned on and provides the selected output voltage Vout, typically at (or below) a maximum Vout that is based on the minimum and maximum voltage and current parameters of the terminal LED lighting apparatuses **150**G, so that at least minimum voltage and current is provided to the terminal LED lighting apparatuses **150**G and the maximum voltage and current of the terminal LED lighting apparatuses **150**G generally is not exceeded, also as discussed above. For example, in an exemplary embodiment, during operation (automatic mode), Voutmax=Vinmin for the terminal LED lighting apparatuses **150**G. Also for example, a Vout may be determined by the central (host) controller **120** to be based upon a selected percentage above the sum of the minimum LED **140** currents for all of the terminal LED lighting apparatus **150**G included within the system **100**A, such as Vout$\propto$1.1Σ minimum I_{LED}, or setting Voutmax=the minimum V_{LED}, or setting the output current of the central (host) power source **125**=1.1Σ minimum I_{LED}, or based upon a range in between minimum and maximum voltage and current levels of the terminal LED lighting apparatuses **150**G, such as maximum $V_{LED} \geq V_{out} \geq$ minimum V_{LED}, or 1.1Σ minimum $I_{LED} \leq$ output current of the central (host) power source **125**$\leq$0.8Σ maximum I_{LED}, etc., for example and without limitation. For this embodiment, the output current and voltage of the central (host) power source **125** also is typically monitored, with feedback provided as discussed above, so that these current and voltage levels are within an acceptable margin and do not exceed the current and voltage limits discussed above for the plurality of terminal LED lighting apparatuses **150**G.

For example, in an exemplary embodiment, during operation (automatic mode), Voutmax=Vinmin for the terminal LED lighting apparatuses **150**G, and the output current of the central (host) power source **125** is monitored such that the output current $\leq$1.1Σ minimum I_{LED}.

FIG. **13** is a block and circuit diagram illustrating a ninth exemplary or representative terminal LED lighting apparatus **150**H for a comparatively low voltage DC system **100**A, such as illustrated in FIG. **5** and discussed above for other terminal LED lighting apparatuses **150**A, **150**F, and **150**G. An exemplary or representative terminal LED lighting apparatus **150**H is coupleable to transmission power lines **195**A, and comprises a terminal (or remote) controller **160**, and a plurality of LEDs **140** coupled to a current source (or regulator) **145**G. For this representative embodiment, the current source (or regulator) **145**G comprises a fuse **432**, a current regulator **440**, and a voltage divider comprising a plurality of resistors **433**, **438**, and **435**, and zener diode **437**, which is utilized to provide operating voltages for the terminal (or remote) controller **160** and the current regulator **440**. The current regulator **440**, for example, may be implemented as a buck converter or a flyback converter, or any other converter or current regulator topology, and may typically comprise an inductor, a MOSFET, a sense resistor, and a diode (as previously illustrated and previously discussed with reference to FIG. **5**), for example and without limitation. For this terminal LED lighting apparatus **150**H embodiment, the fuse **432** also operates as known in the art to open circuit at or above a predetermined LED **140** current, while the operational voltage provided to the current source **436** by the voltage divider components is typically stably fixed by the resistors **435**, **438** and zener diode **437**. The LED **140** current, however, is typically determined by control signals provided to the current regulator **440** by the terminal (or remote) controller **160**, based upon a sensed or measured value of Vin, as discussed above, such as with reference to FIG. **3**, based upon the value of Vout provided by the central (host) power source **125** for a selected dimming level "ρ". Also as discussed above, as an option, such an embodiment may also include in its housing, labeling and/or packaging, machine-readable encoded fields **170** which may be scanned into the central (host) power source **125** during set up or during exchange modes, which will typically include encoded information for minimum and maximum voltage and minimum and maximum current for the terminal LED lighting apparatuses **150**H, and possibly a network address for the apparatus **150**H. As mentioned above, these maximum and minimum voltage and current parameters may also be provided on the basis of minimum and maximum LED **140** voltage levels, and minimum and maximum LED **140** current levels, for the incorporated string of LEDs **140**. These operational parameters may also be manually entered, as discussed above.

A plurality of terminal LED lighting apparatuses **150**H may be utilized in a system **100**A up to the power capacity of the central (host) power source **125**, with operational parameters input into the system **100**A during set up and/or exchange modes as previously discussed. For example, during set up or exchange modes for a first embodiment, minimum and maximum input voltage and minimum and maximum input current levels for the terminal LED lighting apparatus **150**H are typically entered and stored in the central (host) power source **125**. For example, during set up or exchange modes for a second embodiment, maximum input voltage and minimum (and optionally) maximum input current levels for the terminal LED lighting apparatus **150**H are typically entered and stored in the central (host) power source **125**. For either or both embodiments, the central (host) controller **120** then sets Voutmax=Vinmax for the terminal LED lighting apparatuses **150**H, without manual override, and sets a limit for output current from the central (host) power source **125** equal to 1.1Σ minimum I_{LED} for the terminal LED lighting apparatuses **150**H.

During operation (automatic mode), the central (host) power source **125** is turned on and provides the selected output voltage Vout, typically at (or below) the maximum Voutmax that is based on the maximum voltage parameter of the terminal LED lighting apparatuses **150**H. For example, when turned on, the central (host) power source **125** may automatically provide Voutmax, for maximum brightness, or may provide a lower Vout corresponding to its last dimming setting by the user. Concurrently, the central (host) controller **120** monitors output current from the central (host) power source **125** and provides corresponding feedback signals to maintain output current $\leq$1.1Σ minimum I_{LED}, for example, so that the output current levels are within an acceptable margin and do not exceed the current limits discussed above for the plurality of terminal LED lighting apparatuses **150**H. Similarly for this embodiment, in addition to monitoring output current, the output voltage Vout of the central (host) power source **125** also is typically monitored, with feedback provided as discussed above, so that the selected dimming level is provided and further, that the output voltage levels are within an acceptable margin and do not exceed the voltage limits discussed above for the plurality of terminal LED lighting apparatuses **150**H.

FIG. **14** is a block and circuit diagram illustrating a tenth exemplary or representative terminal LED lighting apparatus **150**J for a comparatively low voltage DC system **100**A, such as illustrated in FIG. **5** and discussed above for other terminal LED lighting apparatuses **150**A, **150**F, **150**G, and **150**H. In this exemplary embodiment, the terminal LED lighting apparatus **150**J functions similarly to terminal LED lighting apparatus **150**H, but now includes multiple series-connected (strings) or channels of LEDs **140**, illustrated as channel one LEDs $\mathbf{140}_1$, channel two LEDs $\mathbf{140}_2$, through channel "N" LEDs $\mathbf{140}_N$, each of which is controlled by a corresponding current regulator **440**, illustrated respectively as current regulator $\mathbf{440}_1$, current regulator $\mathbf{440}_2$, through current regulator $\mathbf{440}_N$. Each of the LED **140** channels may provide a different color, color temperature, or other lighting effect, for example and without limitation, such as channel one comprising red LEDs $\mathbf{140}_1$, channel two comprising green LEDs $\mathbf{140}_2$, through channel "N" comprising blue LEDs $\mathbf{140}_N$, etc. There may be any number of LED **140** channels. In turn, each of the various current regulators **440** are separately (and/or independently) controlled by a terminal (or remote) controller **160**A, which has expanded capability to independently control each channel, rather than controlling the current through a single string of LEDs through a single current regulator **440**. In addition, the terminal LED lighting apparatus **150**J optionally includes a remote user interface **165** and one or more sensors **155** (which, for example, may be implemented as current sense resistors (e.g., **402**) within each current regulator **440**, or which may provide additional sensing capabilities).

An exemplary or representative terminal LED lighting apparatus **150**J also is coupleable to transmission power lines **195**A, and comprises a terminal (or remote) controller **160**A, and a plurality of strings of LEDs **140** which are coupled to a current source (or regulator) **145**H. For this representative embodiment, the current source (or regulator) **145**H comprises a fuse **432**, a plurality of current regulators **440**, and a voltage divider comprising a plurality of resistors **433**, **438**, and **435**, and zener diode **437**, which is utilized to provide operating voltages for the terminal (or remote) controller **160**A, the current regulators **440**, the optional remote user interface **165**, and the sensor(s) **155** (depending upon the type of sensor(s) **155** utilized). The current regulators **440**, for example, may be implemented as a buck converter or a flyback converter, or any other converter or current regulator topology, and may typically comprise an inductor, a MOSFET, a sense resistor, and a diode (as previously illustrated and previously discussed with reference to FIG. **5**), for example and without limitation. For this terminal LED lighting apparatus **150**J embodiment, the fuse **432** also operates as known in the art to open circuit at or above a predetermined LED **140** current, while the operational voltage provided to the current source **436** by the voltage divider components is typically stably fixed by the resistors **435**, **438** and zener diode **437**.

The currents of the various LED **140** channels, however, are separately (and/or independently) determined by control signals provided to the respective current regulators **440** by the terminal (or remote) controller **160**. In one exemplary embodiment, the terminal (or remote) controller **160**A may determine each such LED **140** current based upon a sensed or measured value of Vin, as discussed above, such as with reference to FIG. **3**, based upon the value of Vout provided by the central (host) power source **125** for a selected dimming level "ρ". In another exemplary embodiment, the terminal (or remote) controller **160**A may determine each such LED **140** current separately (and/or independently), not only based upon a sensed or measured value of Vin, but also based upon color mixing and color temperature control, for any selected lighting effect, and separate dimming for each LED **140** channel, such as provided through the remote user interface **165** for user control, or through sensor(s) **155** (which may override or supplement the remote control by the user), or as potentially communicated by the central (host) controller **120**, also separately (and/or independently) for each LED **140** channel, such as through additional wiring, wireless communication, or power line signaling as mentioned above.

Also as discussed above, as an option, such an embodiment may also include in its housing, labeling and/or packaging, machine-readable encoded fields **170** which may be scanned into the central (host) power source **125** during set up or during exchange modes, which will typically include, for each LED **140** channel of each terminal LED lighting apparatus **150**J, encoded information for minimum and maximum voltage and minimum and maximum current, and possibly a network address for the apparatus **150**J. As mentioned above, these maximum and minimum voltage and current parameters may also be provided on the basis of minimum and maximum LED **140** voltage levels, and minimum and maximum LED **140** current levels, for each of the incorporated channels of LEDs **140**. These operational parameters may also be manually entered, as discussed above.

A plurality of terminal LED lighting apparatuses **150**J may be utilized in a system **100**A up to the power capacity of the central (host) power source **125**, with operational parameters input into the system **100**A during set up and/or exchange modes as previously discussed. For example, during set up or exchange modes for a first embodiment, minimum and maximum input voltage and minimum and maximum input current levels for the terminal LED lighting apparatus **150**J are typically entered and stored in the central (host) power source **125**. For example, during set up or exchange modes for a second embodiment, maximum input voltage and minimum (and optionally) maximum input current levels for the terminal LED lighting apparatus **150**J are typically entered and stored in the central (host) power source **125**. For either or both embodiments, the central (host) controller **120** then sets Voutmax=Vinmax for the terminal LED lighting apparatuses **150**H, without manual override, and sets a limit for output current from the central (host) power source **125** equal to 1.1Σ minimum I_{LED} for the terminal LED lighting apparatuses **150**J.

During operation (automatic mode), the central (host) power source **125** is turned on and provides the selected output voltage Vout, typically at (or below) the maximum Voutmax that is based on the maximum voltage parameter of the terminal LED lighting apparatuses **150**J. For example, when turned on, the central (host) power source **125** may automatically provide Voutmax, for maximum brightness, or may provide a lower Vout corresponding to its last dimming setting by the user. Concurrently, the central (host) controller **120** monitors output current from the central (host) power source **125** and provides corresponding feedback signals to maintain output current ≤1.1Σ minimum I_{LED}, for example, so that the output current levels are within an acceptable margin and do not exceed the current limits discussed above for the plurality of terminal LED lighting apparatuses **150**J. Similarly for this embodiment, in addition to monitoring output current, the output voltage Vout of the central (host) power source **125** also is typically monitored, with feedback provided as discussed above, so that the selected dimming level is provided and further, that the output voltage levels are within an acceptable margin and do not exceed the voltage limits discussed above for the plurality of terminal LED lighting apparatuses **150**J.

In addition, using one or more terminal LED lighting apparatuses **150**J, via central or remote user interfaces **135**, **165**, a user may select any of a wide range of lighting effects and a wide variety of brightness levels, such as color mixing, color temperature, and various architectural lighting effects, any and all of which may also include different levels of dimming.

FIG. **15** is a diagram illustrating exemplary or representative machine-readable encoded fields **170**, such as barcode fields or QR code fields, for use with an exemplary or representative apparatus, method and system. The machine-readable encoded fields **170** may have any selected, suitable or appropriate format, known or developed in the future, such as the vertical lines, bars and spaces of a linear or matrix UPC barcode, or the various QR encoded fields. As illustrated in FIG. **15**, exemplary machine-readable encoded fields **170** comprises a plurality of fields **501**-**510**, not all of which are required to be used, and many of which may be optional, including one or more power fields, such as maximum or nominal power rating field **501**; one or more voltage fields, such as maximum voltage field **502** and minimum voltage field **503**; one or more current fields, such as maximum current field **504** and minimum current field **505**; a nominal voltage/current field **506**, specifying the LED **140** voltage at nominal current; a minimum dimming level (voltage or current) field **507**; an adjustable color temperature range field **508**; a unique number or identification (I.D.) field **509** for the particular terminal LED lighting apparatus **150**; and a field **510** for any other drive or network parameters. Not separately illustrated in FIG. **15** may be fields for format information, error correction, manufacturer, model number, etc.

As mentioned above, this data input (e.g., scanned) from machine-readable encoded fields **170** will be stored in the controller **120** memory and used for technical purposes to program the central (host) controller **120** as described above. Another application of this information is suggested and may be used for generating lighting reports for the user, with performance metrics over time, and as an example and without limitation, may include any of the various following information, such as: number of terminal LED lighting apparatuses **150** installed and dates of installation; number of terminal LED lighting apparatuses **150** which failed; a listing of failed terminal LED lighting apparatuses **150** with total hours of performance; average annual or daily consumed power, annual, daily, etc.; average daily on time; and average daily dimming level.

In one exemplary or representative embodiment, a user is provided with a retrofitting kit, as mentioned above. Such a retrofitting kit may include a central (host) power source **125**, with or without a dimmer function, having a form factor suitable for replacing a standard lighting or dimmer switch as described above, and one or more terminal LED lighting apparatuses **150** (as LED bulbs) designed to operate in conjunction with the central (host) power source **125**. A user wishing to retrofit a lighting system would be able to easily replace a legacy wall switch with the central (host) power source **125** having a legacy-compatible form factor provided in the retrofitting kit, connecting it properly to the electrical supply line and to the feed lines to the lighting load(s). The terminal LED lighting apparatuses **150** (as LED bulbs) can then be installed in place of the original incandescent of CFL bulbs used as terminators on the feed lines connected to the retrofitted central (host) power source **125**.

In another exemplary embodiment, the retrofitting kit may also include one or more lighting sockets (not separately illustrated) which each have a mating form factor or interface, designed or adapted to fit the form factor or interface of the one or more terminal LED lighting apparatuses **150**. A user wishing to retrofit a lighting system would be able to easily replace existing, legacy lighting sockets with the new sockets having the new mating or otherwise compatible form factor provided in the retrofitting kit, connecting it properly to the feed lines from the central (host) power source **125** (and to any existing ground or neutral).

FIG. **16** is a block and circuit diagram illustrating an eleventh exemplary or representative terminal LED lighting apparatus **150**K for use in a comparatively low voltage DC system with an exemplary or representative first terminal or remote controller **160**A and an exemplary or representative dimming signal generator **520**. FIG. **17** is a block and circuit diagram illustrating an exemplary or representative first dimming signal generator **520**A implemented using analog control, in an exemplary or representative terminal LED lighting apparatus **150**L. FIG. **18** is a block and circuit diagram illustrating an exemplary or representative second dimming signal generator **520**B, implementing combined analog and PWM control, in an exemplary or representative terminal LED lighting apparatus **150**M. LEDs **140** are not separately illustrated in FIG. **16**.

Such an exemplary or representative embodiment provides a terminal LED lighting apparatus **150**K with dimming capability for DC luminaires, lamps or bulbs. Such an exemplary or representative terminal LED lighting apparatus **150**K is illustrated as comprising an exemplary or representative first terminal or remote controller **160**A, an exemplary or representative dimming signal generator **520**, and a current source (or regulator) **145**A with a buck topology comprised of inductor **408**, diode **406**, and MOSFET **404**, using a current sense resistor **402** (illustrated in FIGS. **17** and **18**) as a feedback to the first terminal or remote controller **160**A. The series-connected string of LEDs **140** (illustrated in FIGS. **17** and **18**) is driven by a current regulated source, and the LEDs **140** do not require binning during manufacturing. While a buck converter is illustrated, any other type of converter may be utilized equivalently, including buck-boost, sepic, flyback, and many others currently known or developed in the future.

As illustrated in FIG. **16**, an exemplary or representative first terminal or remote controller **160**A may be implemented as known in the electronic arts and industry, and is illustrated for purposes of example and without limitation, and typically may comprise a frequency set resistor **20**, on-time generator **17**, input for analog dimming **51**, current sense comparators **10** and **11** with reference voltage **22**, PWM comparator **13** with reference voltage **23**, control logic **12**, level shift **15**, high side switch driver **16**, filter capacitor **14**. For example, an exemplary or representative first terminal or remote controller **160**A may be implemented as a Texas Instruments LM3404 integrated circuit. Low voltage DC lines **195**A are illustrated as lines **54** and **55** (which are also coupled to dimming signal generator) **520**).

The dimming signal generator **520** is utilized to control such a first terminal or remote controller **160**A when implemented as such an off-the-shelf component, typically having limited capabilities, such as to enable sophisticated dimming capability in the exemplary DC system. For example, a voltage change on the low voltage DC lines **195**A (such as from 56V to 48V, or from 47V to 40V, as examples of any of a wide variety of DC voltage ranges which may be utilized equivalently) using the dimming signal generator **520**, will generate a change in LED **140** current (100% to 0%) resulting in dimming corresponding to full brightness light output to zero light output. Stated another way, the dimming signal generator **520** will "spoof" or fool the first terminal or remote controller **160**A, by interfering with or modulating feedback signals to the first terminal or remote controller **160**A, and by doing so, will provide significant dimming capability.

Referring to FIG. **17**, the first dimming signal generator **520**A comprises an operational amplifier **64** with a reference voltage **67**, feedback resistor **58**, and one or more voltage dividers, such as a first voltage divider **44** implemented using resistors **56** and **57**, and a second voltage divider implemented using resistors **59** and **60**. Current to the LEDs **140** is provided on line **52** from current source (or regulator) **145**A. Current sense feedback (to line, node or input **51** of the first terminal or remote controller **160**A) of LED **140** current is provided via current sense resistor **402** and resistor **63**.

As mentioned above, a user may control light output in a system **100**, resulting in a change in DC voltage levels on lines **195**A, between a maximum DC voltage level ("Vinmax") and a minimum DC voltage level ("Vinmin") on line **54**. This change in DC voltage may be sensed using resistors **56** and **57** (as a first voltage divider **44**), and provided on input **70** to operational amplifier **64**, which compares this voltage to reference voltage **67** input on line **69**. As the voltage drops across first voltage divider **44** (in comparison to reference voltage **67**), the operational amplifier **64** generates a greater output voltage (V_{68}) on line **68**, as illustrated in FIG. **19**. In addition to increasing the current through resistor **60**, this greater output voltage from the operational amplifier **64** on line **68** also results in increased current through a current path comprising resistors **59**, **63** and **402**, changing the voltage (and/or current) being sensed on current sense resistor **402** via (current) feedback input **51** of the first terminal or remote controller **160**A (i.e., increases the voltage at input or node **51**). As a result, the current feedback to the first terminal or remote controller **160**A (falsely) indicates a greater LED **140** current than actually exists, and in response, the first terminal or remote controller **160**A, controlling the current source (or regulator) **145**A, lowers the current level provided to the LEDs **140** (on line **52**), resulting in the desired dimming of light output. Conversely, when the DC voltage levels on lines **195**A increases (to increase output brightness), the output voltage from the operational amplifier **64** on line **68** will become lower, decreasing the voltage (and/or current) level at input (or node) **51**, making it appear that the LED **140** current has decreased, and in response, the first terminal or remote controller **160**A, controlling the current source (or regulator) **145**A, raises the current level provided to the LEDs **140** (on line **52**), resulting in the desired brightness of light output.

Stated another way, this depth of dimming (for example 1:1000) is executed by changing the input voltage Vin on lines **195**A from Vinmin to Vinmax (for example, 40V to 47V), by controlling the current source **145**A through the first terminal or remote controller **160**A. In the analog embodiment, the first dimming signal generator **520**A, the control is selected by using the current feedback input **51** of the first terminal or remote controller **160**A. The current feedback input **51** (e.g., into comparator **10** of FIG. **16**) has a fixed threshold (V_T) to limit the LED **140** current at a fixed level. To regulate LED **140** current the signal at input **51** is supplied as a sum of the voltage drop across current sense resistor **402** and also across resistor **63**. The voltage at the input **51** is then $V_{51}=V_{402}+V_{63}$, where V_{402} is the voltage across resistor **402**, and V_{63} is the voltage across resistor **63**.

As current feedback keeps V_{51} equal to the threshold voltage V_T, then the LED **140** current, which is proportional to the voltage drop across resistor **402**, will depend on V_{63}, which is

$$V_{63}=(V_{68}-V_{402})*R_{63}/(R_{59}+R_{63}+R_{402})$$

The voltage signal V_{63} is a fraction of voltage signal V_{68} of output of operational amplifier **64**. The divider of voltage V_{68} is made by resistors **59**, **63** and **402**, having resistance values which are selected to provide, at the maximum of output voltage of the operational amplifier **64**, a minimum, repeatable, flicker-free LED **140** current. For example, for an LED **140** having an average current of 400 mA, a maximum operational amplifier **68** voltage of 12 V, and a threshold voltage V_T=0.2V, then resistance values of resistors **59**, **63** and **402** were set as 91K ohm, 1.6K ohm and 0.5 ohm, respectively. The control voltage at the output **68** of the operational amplifier **64** is shown on FIG. **19** as a function of voltage on lines **195**A (line **54**). In order to exclude non equal brightness at different LED bulbs and achieve the maximum range of brightness regulation at a given accuracy of current source **145**A, a flat portion of the regulation characteristic **68**A and **68**B was introduced. As discussed above, when powered on, the central (host) power source **125** will provide an output voltage corresponding to a desired dimming level, which is the input voltage Vin to the terminal LED lighting apparatus **150**A, and which varies between a minimum input voltage Vinmin and a maximum input voltage Vinmax, illustrated as line **251** (FIG. **4**).

To get a desired output signal on line **68** of the operational amplifier **64** (e.g., V_{68}) as a function of input DC voltage Vin, the noninverting input **69** of the operational amplifier **64** is connected to the reference voltage **67**, and its inverting input **70** is coupled to the input voltage Vin via a resistive divider **56**, **57** with a dividing ratio satisfying the following equation:

$$(R_{56}+R_{57})/R_{57}=s_1*\left(\frac{V_{inmin}}{V_{ref}}\right),$$

where Vinmin is the minimum input power transmission line voltage as discussed above; s_1 is a coefficient to create a flat portion of the regulation characteristic at minimum input voltage (**68**A), the values of s_1 are from 0.95 to 0.99 (see FIG. **19**).

Also the operational amplifier **64** has a negative feedback with resistor **58** such that the following equation is valid:

$$(s_2*(V_{outmax}-V_{outmin})*V_{inmin})/V_{ref}*(V_{inmax}-V_{inmin}))=(R_{56}+R_{57})*R_{58}/(R_{56}*R_{57}),$$

Where R_{56}, R_{57}, R_{58} are resistors **56**, **57** and **58** respectively, V_{outmax} and V_{outmin} respectively are the maximum and minimum output signal of the operational amplifier **64**, s_2 is a coefficient between 1.05 to 1.1 to form a flat part (**68**B) of the regulation characteristics at the maximum input voltage (see FIG. **19**).

When the input DC voltage is changing from V_{inmin} to V_{inmax} the output signal on line **68** of the operational amplifier **64** will be changing as shown in FIG. **19** from V_{outmax}, **68**A to V_{outmin}, **68**B with a certain flat regions at the beginning and at the end of characteristic. For example, for an input voltage changing from 40V to 47V the values of resistors R_{56}, R_{57}, R_{58} were selected to be equal to 603K ohm, 189.6K ohm, and 1.1 M ohm, respectively.

A first exemplary or representative method of dimming consists of the following steps:

1. sensing the input voltage;
2. dividing the sensed signal by the ratio

$$\frac{V_{inmin}}{V_{ref}};$$

3. introducing a flat portion of regulation characteristic at minimum input voltage by multiplying this ratio by a coefficient s_1, within 0.95-0.99,

$$s_1 * \left(\frac{V_{inmin}}{V_{ref}}\right);$$

4. applying this signal to an inverting input of the operational amplifier;
5. applying a reference voltage to the noninverting input of the operational amplifier;

6A. keeping operational amplifier negative feedback to satisfy the following equation

$$(V_{outmax}-V_{outmin})*V_{inmin})/V_{ref}*(V_{inmax}-V_{inmin}))=(R_{56}+R_{57})*R_{58}/(R_{56}*R_{57});$$

7. executing analog dimming signal by summing signals across resistors at the control input of the current source with the output signal of operational amplifier and negative feedback signal measured across current sense resistor; and
8. applying the executed analog dimming signal to the current feedback input of the current source

A second exemplary or representative method of dimming will have some additional steps (6B) to compliment the first method. It introduces the flat portion of the regulation characteristic to equalize brightness of different co-located LED bulbs with different accuracy of current control, adding or substituting step 6B, consisting of:

6B. introducing a flat portion of the regulation characteristic by changing the operational amplifier feedback by modifying its gain by coefficient s_2 within 1.05-1.1.

$$(s_2*(V_{outmax}-V_{outmin})*V_{inmin})/V_{ref}*(V_{inmax}-V_{inmin}))=(R_{56}+R_{57})*R_{58}/(R_{56}*R_{57}).$$

Analog dimming allows a fairly wide range of change of the brightness of LEDs **140**. Due to differences of LED characteristics, however, it is difficult to maintain the same brightness levels in a few co-located LED **140** bulbs. To solve that problem, in accordance with exemplary or representative embodiments, the depth of analog dimming is limited and PWM is introduced to change the brightness at low LED **140** current levels, providing the same average current to the LEDs **140**, but using a lower or smaller duty cycle. A second dimming signal generator **520**B is illustrated in FIG. **18**, having combined analog and PWM control, and in addition to the components previously discussed with reference to FIG. **17** and dimming signal generator **520**A, further comprises ramp generator **65**, comparator **66**, and resistor **61** (forming another voltage divider with resistor **60**). The output of comparator **66** on line **73** is connected to a noninverting PWM dimming input **53** (illustrated as noninverting input of operational amplifier **13**) of the first terminal or remote controller **160**A. The PWM output of comparator **66** on line **73** typically has a frequency in the hundreds of Hz range, compared to the much higher frequency (typically kHz to MHz range) of the (buck) converter within the current source **145**A.

FIG. **20** is graphical diagram illustrating (a) a sawtooth waveform, and (b) a PWM signal. As illustrated in FIG. **20**, part (a), the sawtooth voltage is at the input **72** of comparator **66**, with the PWM duty cycle controlled by a signal on line **71** (the inverting input of) comparator **66**, and in part (b), a PWM waveform at the output **73** of the comparator **66**. The output signal of the operational amplifier **64** on line **68**, previously discussed, is also coupled to an inverting input **71** of the comparator **66** via a resistive divider (resistors **60**, **61**) with the gain $k*V_{outmax}=V_{sawtoothmax}$, where $V_{sawtoothmax}$ is the maximum value of the sawtooth voltage generated by a ramp generator **65** and applied to an noninverting input **72** of the comparator **66**. The instantaneous value of the sawtooth signal is being kept between $k*V_{outmax}$ and $k*V_{outmin}$, being maximum $V_{sawtoothmax}$, illustrated at voltage level **72**A in FIG. **20**, and minimum $V_{sawtoothmin}$, illustrated at voltage level **72**B in FIG. **20**.

A third exemplary or representative method of dimming uses PWM control at low current levels of LEDs **140**:

1. generating the output signal of the operational amplifier changing inversely proportional to the input voltage change within a set regulation range;
2. Dividing this signal by the ratio of maximum output of the operational amplifier signal to the amplitude of a sawtooth signal of the ramp generator, $k*V_{outmax}=V_{sawtoothmax}$;
3. Comparing this signal with a sawtooth signal generated by a ramp generator **65** at the PWM comparator **66** to produce a duty cycle of PWM to execute the regulation of LED **140** current/brightness;
4. Applying the generated PWM signal to a noninverting PWM dimming input **53** of the first terminal or remote controller **160**A.

In order to execute PWM dimming, there is no need to have a special PWM input at first terminal or remote controller **160**A. FIG. **21** is a block and circuit diagram illustrating a third dimming signal generator **520**C having combined analog and PWM control, in which the PWM is summed with the analog control signal in an exemplary or representative terminal LED lighting apparatus **150**N, effectively providing a pulse for the analog control signal. The PWM comparator **66** is connected via resistor **74** to the (current) feedback input **51** of the first terminal or remote controller **160**A. The value of resistor **74** is selected such that at a high output signal from the comparator **66** on line **73**, the voltage drop on resistor **74** generated by current of the comparator **66** is adequate to shut down the current source **145**A. For example, at a threshold of current feedback input **51** of 0.2 V, Vcc comparator 12.0V (internal to first terminal or remote controller **160**A and not illustrated separately) and resistor **63** equal 1.6K ohm, the resistor **74** is selected to be 47K ohm, which provides for the current feedback signal to be almost two times higher than the threshold signal for input **51**. The PWM control of the third dimming signal generator **520**C is reversed, so the input **71** is connected to the output of the ramp generator **65** and input **72** is coupled to the connection point of the divider comprising resistors **60** and **61**. FIG. **22** illustrates an exemplary waveform of a PWM signal summed with the analog dimming signal, at the input or node **51** of the first terminal or remote controller **160**A: V**51** is voltage level or signal at the input **51**; V**51**A is the threshold of the current feedback input **51**; and V**51**B is analog dimming signal at the input **51** of first terminal or remote controller **160**A.

FIG. **23** is a graphical diagram illustrating a regulation characteristic of the third dimming signal generator **520**C with combined analog and PWM dimming regulation, illustrating I_{out}, the output current of the current source **145**A versus the input voltage Vin at line **54**, V_{inmin}, **54**A, the minimum input voltage; V_{inmax}, **54**B, the maximum input voltage; and V_{intr}, **54**C, the threshold input voltage, namely, the input voltage at which the combined (summed) PWM and analog dimming starts.

A fourth exemplary or representative method of dimming uses a combined analog and PWM control at low current levels of LEDs **140**:

1. Generating the output signal of the operational amplifier changing inversely proportional to the input voltage change within a set regulation range and executing the analog dimming signal;

2. Applying the executed analog dimming signal to the current feedback input of the current source;

3. Generating a PWM signal by comparing a ramp generator signal with the output signal of the operational amplifier; and

4. Applying the generated PWM signal to the current feedback input of the current source, adding it to the analog dimming signal.

FIG. **24** is a block and circuit diagram illustrating an exemplary or representative fourth dimming signal generator **520**D with analog dimming regulation and in parallel with LEDs **140**, a resistive network (implemented using one or more resistors **78**) controlled by a MOSFET **77** or another type of switch (e.g., bipolar transistor **79** of FIG. **25**), in an exemplary or representative terminal LED lighting apparatus **150**P. In order to increase the accuracy and stability of dimming at low LED **140** current levels, in accordance with an exemplary embodiment, part of the current from the LED **140** is diverted into a parallel, controlled resistive network (resistor **78**) using a MOSFET **77**. The MOSFET **77** is also driven by the output signal of the operational amplifier **64** divided by resistor network **75** and **76** (as another voltage divider). The values of resistors **75** and **76** are selected such that the MOSFET **77** is turning on gradually at about 0.7-0.9 V_{outmax} or 70-90% of the output signal of the operational amplifier. For example, for MOSFET **77** with a gate threshold of 2.0 V the resistance value of resistor **75** is 1.0M ohm and resistor **76** is 300K ohm. Diverting LED **140** current into a parallel resistive network keeps the analog dimming signal applied to current feedback input higher than without parallel network and above noise signals, thereby making dimming regulation more stable.

Gradual turning on/off of the MOSFET **77** does not compromise the smoothness of dimming, as it is effectively invisible to the human eye. The extracting of LED **140** current is proportional to the conductance of the parallel network and LEDs **140**. The conductance of the parallel network is established by a conductance of the field channel of the MOSFET **77** and a series connected current limiting resistor **78**. The value of this resistor **78** sets the minimum LED **140** current. Minimum LED current would be defined by the targeted minimum LED brightness or minimum brightness without low DC current LED flickering. For example, for a network of 12 series connected LEDs **140** (about 36.0 V forward voltage) and dimming depth 1:2000, the resistance value of resistor **78** is selected as a 1.2K ohm resistor.

FIG. **25** is a block and circuit diagram illustrating an exemplary or representative fifth dimming signal generator **520**E with analog dimming regulation and in parallel with LEDs **140**, a resistive network controlled by a bipolar transistor **79**, in an exemplary or representative terminal LED lighting apparatus **150**Q, and functions effectively identically to the dimming signal generator **520**D discussed above. The bipolar transistor **79** is also driven by the output signal of the operational amplifier **64** divided by resistor network or resistors **75** and **76**. The resistance values of resistors **75** and **76** are also selected such that the bipolar transistor **79** is turning on gradually at about 0.7-0.9 V_{outmax} or 70-90% of the output signal of the operational amplifier. For example, for a bipolar transistor **79** with a base-emitter threshold of 0.6 V, the resistance value of resistor **75** is 510K ohm and resistor **76** is 51K ohm. The extracting of LED **140** current is also proportional to the conductance of parallel network and LEDs **140**. The conductance of the parallel network is established by a conductance of the emitter-collector of the bipolar transistor **79** and a series connected current limiting resistor **78**. The value of this resistor sets the minimum LED current. Minimum LED current would be defined by the targeted minimum LED brightness or minimum brightness without low DC current LED flickering. For example for a network of 12 series connected LEDs (about 36.0 V forward voltage) and dimming depth 1:2000, the resistance value of resistor **78** is selected as 1.1K ohms.

FIG. **26** is a block and circuit diagram illustrating an exemplary or representative sixth dimming signal generator **520**F having combined analog and PWM control, in which the PWM is summed with the analog control signal, and in parallel with LEDs **140**, a resistive network controlled by a MOSFET **77**, in an exemplary or representative terminal LED lighting apparatus **150**R. FIG. **27** is a block and circuit diagram illustrating an exemplary or representative seventh dimming signal generator **520**G having combined analog and PWM control, in which the PWM is summed with the analog control signal, and in parallel with LEDs **140**, a resistive network controlled by a bipolar transistor **79**, in an exemplary or representative terminal LED lighting apparatus **150**S. The analog dimming is executed by the operational amplifier **64** and PWM dimming by ramp generator **65** and PWM comparator **66**. The parallel resistive network operate as previously described with reference to FIGS. **24** and **25**.

FIG. **28** is a flow diagram illustrating a method of providing dimming regulation, and is a useful summary. Beginning with start step **600**, the method senses the input DC voltage level, step **605**, such as by using a voltage divider (resistors **56**, **57**), and senses the LED **140** current level, step **610**, such as by using a current sense resistor **402** and measuring or sensing the corresponding voltage level. The input DC voltage level is compared to a reference voltage level, step **615**, and a corresponding comparison output signal is generated, step **620**, such as by a comparator **64**. As an option, a ramp (or sawtooth) signal is also generated, step **625**, such as by ramp generator **65**, and the ramp signal is compared with the comparison output signal, step **630**, such as by comparator **66**, also as an option. A PWM signal is generated from the ramp signal comparison, step **635**, which optionally also may be provided to the current regulator (**145**A) providing current to the LEDs **140** or to the first terminal or remote controller **160**A controlling the current regulator **145**A. The comparison output signal is combined with the sensed LED current level (e.g., as a summed voltage across resistors **63** and **402**), and potentially also combined with the PWM signal in various embodiments, to form a combined signal, step **640**. The combined signal is then provided as feedback for LED **140** current regulation, step **645**, such as at node or line **51**, and optionally in step **645**, the PWM signal may be provided as a separate signal for LED **140** current regulation. In response, the LED **140** current may be adjusted, step **650**. The method may continue iteratively, returning to step **605**, or when the terminal lighting apparatus **150** is turned off, step **655**, the method may end, return step **660**.

It should be noted that as may be apparent to those having skill in the electronic arts, various components may be substituted equivalently for those illustrated in the various Figures. For example, comparators may be substituted for operational amplifiers **64**, **66**, and other types of voltage and current sensors may be utilized as well. All such variations are considered equivalent and within the scope of the present disclosure.

The present disclosure is to be considered as an exemplification of the principles of the invention and is not intended to limit the invention to the specific embodiments illustrated. In this respect, it is to be understood that the invention is not limited in its application to the details of construction and to the arrangements of components set forth above and below, illustrated in the drawings, or as described in the examples. Systems, methods and apparatuses consistent with the present invention are capable of other embodiments and of being practiced and carried out in various ways.

Although the invention has been described with respect to specific embodiments thereof, these embodiments are merely illustrative and not restrictive of the invention. In the description herein, numerous specific details are provided, such as examples of electronic components, electronic and structural connections, materials, and structural variations, to provide a thorough understanding of embodiments of the present invention. One skilled in the relevant art will recognize, however, that an embodiment of the invention can be practiced without one or more of the specific details, or with other apparatus, systems, assemblies, components, materials, parts, etc. In other instances, well-known structures, materials, or operations are not specifically shown or described in detail to avoid obscuring aspects of embodiments of the present invention. In addition, the various Figures are not drawn to scale and should not be regarded as limiting.

Those having skill in the electronic arts will recognize that the various single-stage or two-stage converters may be implemented in a wide variety of ways, in addition to those illustrated, such as flyback, buck, boost, and buck-boost, for example and without limitation, and may be operated in any number of modes (discontinuous current mode, continuous current mode, and critical conduction mode), any and all of which are considered equivalent and within the scope of the present invention.

Reference throughout this specification to "one embodiment", "an embodiment", or a specific "embodiment" means that a particular feature, structure, or characteristic described in connection with the embodiment is included in at least one embodiment of the present invention and not necessarily in all embodiments, and further, are not necessarily referring to the same embodiment. Furthermore, the particular features, structures, or characteristics of any specific embodiment of the present invention may be combined in any suitable manner and in any suitable combination with one or more other embodiments, including the use of selected features without corresponding use of other features. In addition, many modifications may be made to adapt a particular application, situation or material to the essential scope and spirit of the present invention. It is to be understood that other variations and modifications of the embodiments of the present invention described and illustrated herein are possible in light of the teachings herein and are to be considered part of the spirit and scope of the present invention.

It will also be appreciated that one or more of the elements depicted in the Figures can also be implemented in a more separate or integrated manner, or even removed or rendered inoperable in certain cases, as may be useful in accordance with a particular application. Integrally formed combinations of components are also within the scope of the invention, particularly for embodiments in which a separation or combination of discrete components is unclear or indiscernible. In addition, use of the term "coupled" herein, including in its various forms such as "coupling" or "couplable", means and includes any direct or indirect electrical, structural or magnetic coupling, connection or attachment, or adaptation or capability for such a direct or indirect electrical, structural or magnetic coupling, connection or attachment, including integrally formed components and components which are coupled via or through another component.

As used herein for purposes of the present invention, the term "LED" and its plural form "LEDs" should be understood to include any electroluminescent diode or other type of carrier injection- or junction-based system which is capable of generating radiation in response to an electrical signal, including without limitation, various semiconductor- or carbon-based structures which emit light in response to a current or voltage, light emitting polymers, organic LEDs, and so on, including within the visible spectrum, or other spectra such as ultraviolet or infrared, of any bandwidth, or of any color or color temperature.

A "controller" or "processor" **120**, **160** may be any type of controller or processor circuitry, and may be embodied as one or more controllers **120**, **160** configured, designed, programmed or otherwise adapted to perform the functionality discussed herein, using any selected or desired analog or digital circuitry, such as using one or more comparators, operational amplifiers, integrators, capacitors, resistors, switches, digital logic, etc. (not separately illustrated), for example and without limitation, as generally known in the electronic and electrical arts. As the term controller or processor is used herein, a controller **120**, **160**, may include use of a single integrated circuit ("IC"), or may include use of a plurality of integrated circuits or other components connected, arranged or grouped together, such as controllers, microprocessors, digital signal processors ("DSPs"), parallel processors, multiple core processors, custom ICs, application specific integrated circuits ("ASICs"), field programmable gate arrays ("FPGAs"), adaptive computing ICs, associated memory (such as RAM, DRAM and ROM), and other ICs and components, whether analog or digital. As a consequence, as used herein, the term controller (or processor) should be understood to equivalently mean and include a single IC, or arrangement of custom ICs, ASICs, processors, microprocessors, controllers, FPGAs, adaptive computing ICs, or some other grouping of integrated circuits which perform the functions discussed below, with associated memory, such as microprocessor memory or additional RAM, DRAM, SDRAM, SRAM, MRAM, ROM, FLASH, EPROM or EPROM. A controller (or processor) (such as controller **120**, **160**), with its associated memory, may be adapted or configured (via programming, FPGA interconnection, or hard-wiring) to perform the methodology of the invention, as discussed below. For example, the methodology may be programmed and stored, in a controller **120**, **160** with its associated memory (and/or memory **115**) and other equivalent components, as a set of program instructions or other code (or equivalent configuration or other program) for subsequent execution when the processor is operative (i.e., powered on and functioning). Equivalently, when the controller **120**, **160** may implemented in whole or part as FPGAs, custom ICs and/or ASICs, the FPGAs, custom ICs or ASICs also may be designed, configured and/or hard-wired to implement the methodology of the invention. For example, the controller **120**, **160** may be implemented as an arrangement of analog and/or digital circuits, controllers, microprocessors, DSPs and/or ASICs, collectively referred to as a "controller", which are respectively hard-wired, programmed, designed, adapted or configured to implement the methodology of the invention, including possibly in conjunction with a memory **115**.

The optional memory **115**, which may include a data repository (or database), may be embodied in any number of forms, including within any computer or other machine-readable data storage medium, memory device or other storage or communication device for storage or communication of information, currently known or which becomes available in the future, including, but not limited to, a memory integrated circuit ("IC"), or memory portion of an integrated circuit (such as the resident memory within a controller **120**, **160** or processor IC), whether volatile or non-volatile, whether removable or non-removable, including without limitation RAM, FLASH, DRAM, SDRAM, SRAM, MRAM, FeRAM, ROM, EPROM or EPROM, or any other form of memory device, such as a magnetic hard drive, an optical drive, a magnetic disk or tape drive, a hard disk drive, other machine-readable storage or memory media such as a floppy disk, a CDROM, a CD-RW, digital versatile disk (DVD) or other optical memory, or any other type of memory, storage medium, or data storage apparatus or circuit, which is known or which becomes known, depending upon the selected embodiment. The memory **115** may be adapted to store various look up tables, parameters, coefficients, other information and data, programs or instructions (of the software of the present invention), and other types of tables such as database tables.

As indicated above, the controller **120**, **160** is hard-wired or programmed, using software and data structures of the invention, for example, to perform the methodology of the present invention. As a consequence, the system and method of the present invention may be embodied as software which provides such programming or other instructions, such as a set of instructions and/or metadata embodied within a non-transitory computer readable medium, discussed above. In addition, metadata may also be utilized to define the various data structures of a look up table or a database. Such software may be in the form of source or object code, by way of example and without limitation. Source code further may be compiled into some form of instructions or object code (including assembly language instructions or configuration information). The software, source code or metadata of the present invention may be embodied as any type of code, such as C, C++, SystemC, LISA, XML, Java, Brew, SQL and its variations (e.g., SQL 99 or proprietary versions of SQL), DB2, Oracle, or any other type of programming language which performs the functionality discussed herein, including various hardware definition or hardware modeling languages (e.g., Verilog, VHDL, RTL) and resulting database files (e.g., GDSII). As a consequence, a "construct", "program construct", "software construct" or "software", as used equivalently herein, means and refers to any programming language, of any kind, with any syntax or signatures, which provides or can be interpreted to provide the associated functionality or methodology specified (when instantiated or loaded into a processor or computer and executed, including the controller **120**, **160** for example).

The software, metadata, or other source code of the present invention and any resulting bit file (object code, database, or look up table) may be embodied within any tangible, non-transitory storage medium, such as any of the computer or other machine-readable data storage media, as computer-readable instructions, data structures, program modules or other data, such as discussed above with respect to the memory **160**, e.g., a floppy disk, a CDROM, a CD-RW, a DVD, a magnetic hard drive, an optical drive, or any other type of data storage apparatus or medium, as mentioned above.

In the foregoing description and in the Figures, sense resistors are shown in exemplary configurations and locations; however, those skilled in the art will recognize that other types and configurations of sensors may also be used and that sensors may be placed in other locations. Alternate sensor configurations and placements are within the scope of the present invention.

As used herein, the term "DC" denotes both fluctuating DC (such as is obtained from rectified AC) and constant voltage DC (such as is obtained from a battery, voltage regulator, or power filtered with a capacitor). As used herein, the term "AC" denotes any form of alternating current with any waveform (sinusoidal, sine squared, rectified sinusoidal, square, rectangular, triangular, sawtooth, irregular, etc.) and with any DC offset and may include any variation such as chopped or forward- or reverse-phase modulated alternating current, such as from a dimmer switch.

With respect to sensors, we refer herein to parameters that "represent" a given metric or are "representative" of a given metric, where a metric is a measure of a state of at least part of the regulator or its inputs or outputs. A parameter is considered to represent a metric if it is related to the metric directly enough that regulating the parameter will satisfactorily regulate the metric. For example, the metric of LED current may be represented by an inductor current because they are similar and because regulating an inductor current satisfactorily regulates LED current. A parameter may be considered to be an acceptable representation of a metric if it represents a multiple or fraction of the metric. It is to be noted that a parameter may physically be a voltage and yet still represents a current value. For example, the voltage across a sense resistor "represents" current through the resistor.

In the foregoing description of illustrative embodiments and in attached figures where diodes are shown, it is to be understood that synchronous diodes or synchronous rectifiers (for example relays or MOSFETs or other transistors switched off and on by a control signal) or other types of diodes may be used in place of standard diodes within the scope of the present invention. Exemplary embodiments presented here generally generate a positive output voltage with respect to ground; however, the teachings of the present invention apply also to power converters that generate a negative output voltage, where complementary topologies may be constructed by reversing the polarity of semiconductors and other polarized components.

For convenience in notation and description, a transformers may be referred to as a "transformer," although in illustrative embodiments, it may behave in many respects also as an inductor. Similarly, inductors, using methods known in the art, can, under proper conditions, be replaced by transformers. We refer to transformers and inductors as "inductive" or "magnetic" elements, with the understanding that they perform similar functions and may be interchanged within the scope of the present invention.

Furthermore, any signal arrows in the drawings/Figures should be considered only exemplary, and not limiting, unless otherwise specifically noted. Combinations of components of steps will also be considered within the scope of the present invention, particularly where the ability to separate or combine is unclear or foreseeable. The disjunctive term "or", as used herein and throughout the claims that follow, is generally intended to mean "and/or", having both conjunctive and disjunctive meanings (and is not confined to an "exclusive or" meaning), unless otherwise indicated. As used in the description herein and throughout the claims that follow, "a", "an", and "the" include plural references unless the context clearly dictates otherwise. Also as used in the description herein and throughout the claims that follow, the meaning of "in" includes "in" and "on" unless the context clearly dictates otherwise.

The foregoing description of illustrated embodiments of the present invention, including what is described in the summary or in the abstract, is not intended to be exhaustive or to limit the invention to the precise forms disclosed herein. From the foregoing, it will be observed that numerous variations, modifications and substitutions are intended and may be effected without departing from the spirit and scope of the novel concept of the invention. It is to be understood that no limitation with respect to the specific methods and apparatus illustrated herein is intended or should be inferred. It is, of course, intended to cover by the appended claims all such modifications as fall within the scope of the claims.

It is claimed:

1. A dimming signal generator coupleable to a controller or a current generator for a plurality of light emitting diodes (LEDs), the dimming signal generator comprising:

a first resistive voltage divider to sense an input DC voltage;

a current sensor to sense a current level of the plurality of LEDs;

a first operational amplifier coupled to the first resistive voltage divider, the first operational amplifier to compare the sensed input DC voltage to a reference voltage level, and to provide a comparator output signal; and

a current path coupled to an output of the first operational amplifier to combine the comparator output signal with the sensed LED current level to provide a combined signal for current level feedback for control of the LED current level.

2. The dimming signal generator of claim **1**, further comprising:

a ramp signal generator; and

a second operational amplifier coupled to the ramp signal generator and to the output of the first operational amplifier, the second operational amplifier to provide a pulse width modulated signal.

3. The dimming signal generator of claim **2**, wherein the second operational amplifier is further coupled to an input of the controller to provide the pulse width modulated signal directly to the controller for pulse width modulation of the LED current.

4. The dimming signal generator of claim **2**, wherein the second operational amplifier is further coupled to the current path to combine the pulse width modulated signal into the combined signal.

5. The dimming signal generator of claim **2**, wherein the second operational amplifier is to compare the ramp signal with the comparator output signal to generate the pulse width modulated signal.

6. The dimming signal generator of claim **1**, further comprising:

a resistive network coupleable in parallel with the plurality of LEDs;

a second resistive voltage divider coupled to the output of the first operational amplifier; and

a switch coupled to the resistive network and to the second resistive voltage divider to divert current from the plurality of LEDs in response to the comparator output signal.

7. The dimming signal generator of claim **6**, wherein the switch is a MOSFET or a bipolar transistor.

8. The dimming signal generator of claim **1**, wherein the comparator output signal is inversely proportional to the sensed input DC voltage level.

9. The dimming signal generator of claim **1**, wherein the combined signal is greater than the sensed LED current level to cause a decrease in the LED current level and provide dimming of the LEDs.

10. A dimming signal generator coupleable to a controller or a current generator for a plurality of light emitting diodes (LEDs), the dimming signal generator comprising:

a first resistive voltage divider to sense an input DC voltage;

a current sensor to sense a current level of the plurality of LEDs;

a first operational amplifier coupled to the first resistive voltage divider, the first operational amplifier to compare the sensed input DC voltage to a reference voltage level, and to provide a comparator output signal;

a ramp signal generator;

a second operational amplifier coupled to the ramp signal generator and to the output of the first operational amplifier, the second operational amplifier to compare the ramp signal with the comparator output signal to generate a pulse width modulated signal; and

a current path coupled to an output of the first operational amplifier to combine the comparator output signal with the sensed LED current level to provide a combined signal for current level feedback for control of the LED current level.

11. The dimming signal generator of claim **10**, wherein the second operational amplifier is further coupled to an input of the controller to provide the pulse width modulated signal directly to the controller for pulse width modulation of the LED current.

12. The dimming signal generator of claim **10**, wherein the second operational amplifier is further coupled to the current path to combine the pulse width modulated signal into the combined signal.

13. The dimming signal generator of claim **10**, further comprising:

a resistive network coupleable in parallel with the plurality of LEDs;

a second resistive voltage divider coupled to the output of the first operational amplifier; and

a switch coupled to the resistive network and to the second resistive voltage divider to divert current from the plurality of LEDs in response to the comparator output signal.

14. The dimming signal generator of claim **13**, wherein the switch is a MOSFET or a bipolar transistor.

15. A light emitting apparatus comprising:

a plurality of light emitting diodes (LEDs);

a current generator coupled to the plurality of LEDs;

a controller coupled to the current generator; and

a dimming signal generator coupled to the controller, the dimming signal generator to provide a combined signal for current level feedback for control of the LED current level.

16. The light emitting apparatus of claim **15**, wherein the dimming signal generator further comprises:

a first resistive voltage divider to sense an input DC voltage;

a current sensor to sense a current level of the plurality of LEDs;

a first operational amplifier coupled to the first resistive voltage divider, the first operational amplifier to compare the sensed input DC voltage to a reference voltage level, and to provide a comparator output signal; and a current path coupled to an output of the first operational amplifier to combine the comparator output signal with the sensed LED current level to provide the combined signal.

17. The light emitting apparatus of claim **16**, wherein the dimming signal generator further comprises:

a ramp signal generator; and

a second operational amplifier coupled to the ramp signal generator and to the output of the first operational amplifier, the second operational amplifier to provide a pulse width modulated signal.

18. The light emitting apparatus of claim **17**, wherein the second operational amplifier is further coupled to the current path to combine the pulse width modulated signal into the combined signal.

19. The light emitting apparatus of claim **16**, wherein the dimming signal generator further comprises:

a resistive network coupleable in parallel with the plurality of LEDs;

a second resistive voltage divider coupled to the output of the first operational amplifier; and

a switch coupled to the resistive network and to the second resistive voltage divider to divert current from the plurality of LEDs in response to the comparator output signal.

20. A method of providing brightness dimming of a plurality of light emitting diodes (LEDs), the method comprising:

sensing an input DC voltage level;

sensing an LED current level;

using a first operational amplifier, comparing the input DC voltage level to a reference voltage and generating a comparator output signal;

combining the comparator output signal with the sensed LED current level and pulse width modulation signal to form a combined signal;

providing the combined signal as feedback for LED current regulation; and

adjusting the LED current in response to the combined signal.

21. The method of claim **20**, further comprising:

generating a ramp signal;

using a second operational amplifier, generating a pulse width modulation signal.

22. The method of claim **21**, further comprising:

providing the pulse width modulated signal directly to a controller for pulse width modulation of the LED current.

23. The method of claim **21**, further comprising:

combining the pulse width modulated signal into the combined signal.

24. The method of claim **21**, wherein the step of generating the pulse width modulation signal further comprises comparing the ramp signal with the comparator output signal.

25. The method of claim **20**, further comprising:

using a switch, diverting current from the plurality of LEDs in response to the comparator output signal.

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